AN ABSTRACT OF THE THESIS OF

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Title: Irrigation Choices for Major West Coast Crops: Water Scarcity and Climatic Determinants

Abstract approved: ____
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Recent climate change forecasts have aroused growing interest in the influence of water scarcity and climate 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. Given the sensitivity of agricultural production to water scarcity and climate, understanding their influence on irrigation choices is a key contribution to policy evaluation.

This paper addresses the impact of water scarcity and climate 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). Crop-specific modeling provides 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.

The most important policy implications that are found involve asset heterogeneity and the distributional impacts of agricultural policy. Several findings provide valuable information about how irrigators would respond and adapt to climate change. The current findings also lead to

commonly advocated revisions to federal water subsidy policies. Some key differences between the irrigation choices of higher- and lower-value crops are also identified. Identifying these differences sheds further light on the distributional consequences of agricultural policy. Many findings from this research 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, the data used in this research has a large degree of variation in water scarcity and climate, making the findings applicable to other Mediterranean climates in the world.

It is found that specific crops have a proclivity for certain irrigation technologies that can mitigate particular climatic stressors (i.e., frost damage and heat stress). For example, the results indicate that water pricing policies will tend not to encourage water conservation by technology adoption for many orchards, vineyards, and vegetable farms, thereby imposing pure costs to these producers. In essence, climate heterogeneity limits options available to farmers and reduces the set of production technologies that a farm can use. This finding exemplifies that with climate heterogeneity, the distribution of water policy impacts depends on prior land allocation decisions such as crop choices. Heterogeneity in land quality is also found to have important influences on TC.

The effects of temperature on irrigation choices are found to be more profound than the effects of precipitation. Because of the large study region used, the effects of temperature and precipitation on irrigation choices are often found to be quadratic-like. These quadratic-like relationships reveal thresholds where irrigators begin to respond very differently to climate. However, this was not the case for all crops. Thus, it is demonstrated that the effects of climate on irrigation choices are crop-dependent.

The results indicate that for several crops, the discontinuance of irrigation water (i.e., water supply or price uncertainty) creates an option value that delays and discourages adoption of water-saving technologies. The discontinuance of irrigation water is also shown to reduce water demand at the farm-level extensive proportion (i.e., PI) and crop-level intensive margin (i.e., AR). Water price is found to impact all three irrigation choices as well. Well depth is found to facilitate adoption of water-saving technologies for several crops.

This paper demonstrates 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 exhibit important influences on irrigation choices. By using crop-specific equations, quadratic climate variables, and a study region with large variation in climate conditions, this research resolves many inconsistent findings regarding the determinants of irrigation choices. Furthermore, this study establishes a research agenda for crop-specific analysis of irrigation choices. Some of the estimated results warrant verification with further studies. Future crop-specific irrigation choice studies would benefit from panel micro data 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.

Irrigation Choices for Major West Coast Crops: Water Scarcity and Climatic Determinants

by
Beau Olen

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Beau Olen, Author

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Most importantly, the deepest thanks go to my mother Joan Twining Moore. Thank you for the love, support, advice, understanding, and inspiration that I needed to succeed, throughout life and during the writing the writing of this thesis. We did it, Mom!

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX TABLES

DEDICATION

I dedicate this work to the honor of Melvin, Stanley, and Gladys Marple. In loving memory of Melvin, I have such respect for the dedication you showed to my mother during my turbulent adolescent years. I wish that we could have developed a stronger relationship now that I am an adult. I express my sincerest gratitude to Stanley and Gladys. Thank you for the support through tough times. Stanley, the advice and understanding that you provided in relation to your own graduate experience have been so influential to my development. I think of you as a father figure and a friend, Stanley.

Irrigation Choices for Major West Coast Crops: Water Scarcity and Climatic Determinants[1,2]

Introduction

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 these mountain ranges 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 on the West Coast for two reasons. Firstly, diminished dry season streamflows will reduce available water for diversion (Vano 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, thereby reducing water stored for dry-season uses (Hayhoe et al. 2004).[3]

Several cultural factors will contribute to future water scarcity on the West Coast. 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 streamflows for biological 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 expected to impact the yield and quality of agricultural commodities on the West Coast (Adams, Wu, and Houston 2001; 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 (i.e., PI), adopting water-saving irrigation technologies (i.e., TC), and adjusting water application rates for specific crops (i.e., AR).[4,5]

The economic literature has indeed found that irrigators adjust PI, TC, and AR in response to water scarcity and climatic conditions. 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) have been found to facilitate the adoption of water-saving technologies. Moore, Gollehon, and Carey (1994) showed that irrigators adjust water application rates for particular crops in response to climatic conditions.

Despite these efforts, there is a paucity of economic literature providing holistic studies that analyze multiple irrigation choices, let alone the water scarcity and climatic determinants of those choices (see Moore, Gollehon, and Carey (1994) for an exception). Furthermore, there is a dearth of economic literature investigating whether there is a quadratic-like relation between climate and irrigation choices (see Moreno and Sunding (2005) for an exception). The economic literature has acknowledged that climatic stress such as frost damage impact TC (Negri and Brooks 1990; Moreno and Sunding 2005). However, the economic literature has failed to explicitly identify how climatic stress (e.g., frost damage and heat stress) affect irrigation choices.

Regional studies have demonstrated that climate has a quadratic-like relation with agricultural yields and crop-choices. Schlenker and Roberts (2008) investigated the effect of temperature on cotton and non-irrigated corn and soybean yields in the United States. They demonstrated that temperature has an inverted-U shaped relation with cotton, corn, and soybean yields. Schlenker and Roberts (2008) also find that for non-irrigated crops (i.e., corn and soybeans), yield has an inverted-U shaped relation with precipitation. Seo and Mendelsohn (2008) found that for certain crops grown in South America, temperature and precipitation have a quadratic-like relation with crop choice. 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 provide adaptation benefits at diminishing rates.

Heat stress can reduce yield and quality of several major West Coast crops. Agronomic literature has found that above-canopy sprinkler irrigation technologies can mitigate heat stress by providing evaporative cooling of crops and their surrounding microclimates. Frost damage can also diminish yield and quality of fruits, nuts, and vegetables. Agronomic literature has demonstrated that crop frost damage can be mitigated by using above-canopy sprinkler irrigation technologies. Given the sensitivity of agricultural production to water scarcity and climate, understanding their influence on irrigation choices is a key contribution to policy evaluation.

Objectives

Recent climate change forecasts have aroused growing interest in the influence of water scarcity and climate on agricultural production and irrigation practice. This paper addresses the impact of water scarcity and climate 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). This paper seeks findings that provide valuable insights for the design of agricultural policy and how irrigators would respond and adapt to future climate change.

Crop-specific modeling offers a means for identifying climate susceptibilities and estimating their effect on irrigation choices for particular crops. However, it is common in the economic literature to aggregate disparate crops when modeling irrigation choices. Because different crops have different climate susceptibilities and varying thresholds where stress is incurred (Rötter and van de Geijn 1999), highly crop-aggregated models confound the crop-specific effects of water scarcity and climate that govern irrigation choices. The advantage of studies that estimate multiple crop-specific models, as is done in the current research, 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.

Study Region

The West Coast Landscape

The United States West Coast (i.e., California, Oregon, and Washington) is a highly diverse landscape. The West Coast occupies a north-south transect spanning 1,500 miles and 17° of latitude, with area greater than 330,000 square miles. Substantial climatic influences are introduced by the coast, which defines its western border, desert landscapes in the south and northeast, and an extensive network of mountain ranges (Figures 1-3). The coast is typically cooler than many inland landscapes and moderates many climate fluctuations such as differences between daily maximum and minimum temperature. Arid, warmer, desert landscapes are found in southern California and in areas east of the Cascade Mountains in Oregon and Washington. Mountain landscapes receive greater precipitation and have cooler temperatures than lowlands of the West Coast.

The most prominent mountains in the region are the Sierra Nevada and Cascades. The Sierra Nevada Mountains run north-south along the eastern edge of California's Central Valley, with Nevada to their east (Figure 3). California's coastal mountains run north-south between the Central Valley and the coastline. The Central Valley is arguably the most prolific agricultural production region in the in the world.

The Oregon Cascades stretch along the eastern border of the Willamette Valley, a highly diversified agricultural production region (Figure 2). The Cascades continue north into Washington and cut north-northeast of the Olympic Peninsula toward Vancouver, British Columbia (Figure 3). The fertile Columbia River Valley is east-southeast of the Washington Cascades. Oregon and Washington also have a coastal mountain range that defines the western limit of the state and the Willamette Valley, and continue north into the Olympic Peninsula. The coastal mountains, with the exception of Washington's Mount Olympia, are older, more eroded, and lower in elevation than the Sierra Nevada and Cascades. Mountain snowpack is greater in the higher elevation mountains of the West Coast. The Wallowa Mountains border the southeast corner of the Columbia River Valley and stretch south-southeast of Pendleton, Oregon to the Snake River along the Oregon-Idaho border.

The West Coast is the most climatically diverse region in the United States. This climatic diversity contributes to the region's large variation in water scarcity. The West Coast's physical diversity (climate, water scarcity, geography) coincides with remarkable social diversity (institutional and demographic) across jurisdictions and farmers in the region. The region's high degree of variation in physical and social conditions, and the economic relevance of its agricultural economy make it a particularly interesting region for analyzing the determinants of agricultural production decisions, such as irrigation choices.

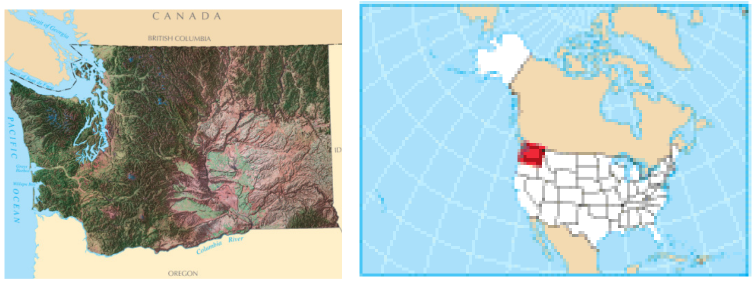

Figure 1. Topographical and Locator Maps for Washington. Maps are not drawn to scale. Source: The National Atlas of the USA; available at: http://www.nationalatlas.gov/.

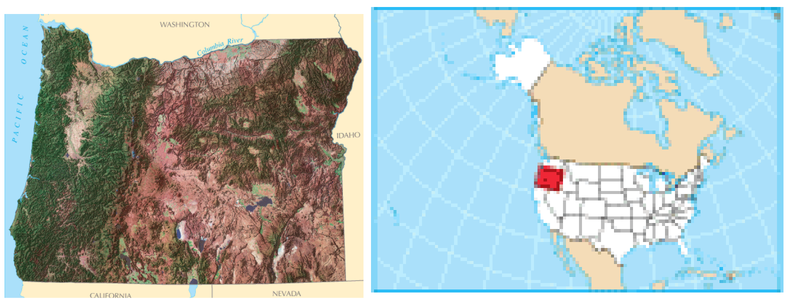

Figure 2. Topographical and Locator Maps for Oregon. Maps are not drawn to scale. Source: The National Atlas of the USA; available at http://www.nationalatlas.gov/.

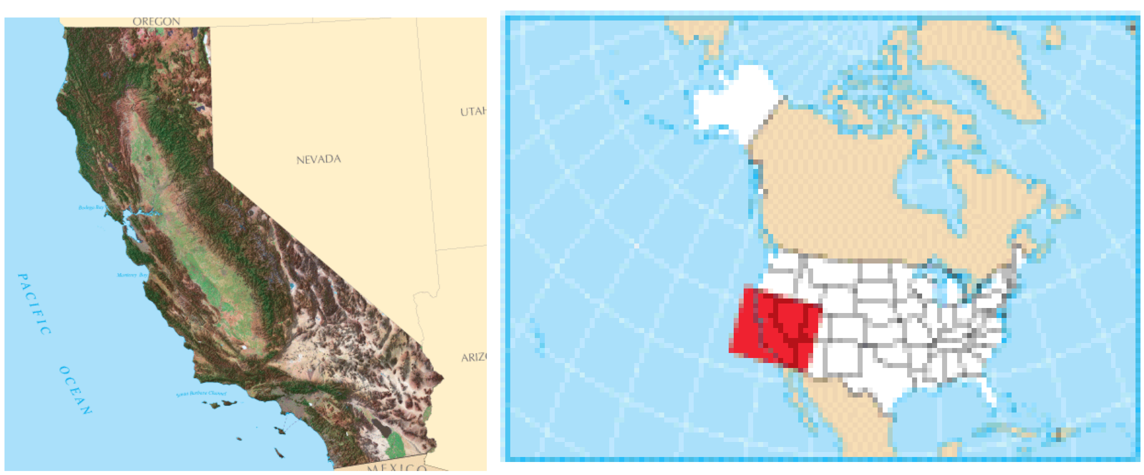

Figure 3. Topographical and Locator Maps for California. Maps are not drawn to scale. Source: The National Atlas of the USA; available at http://www.nationalatlas.gov/.

The West Coast Agricultural Economy

California

California houses some of the nation's most productive and diverse agricultural lands. California commercially produces more than 400 agricultural commodities (CDFA 2010a) and has led all states in agricultural sales since 1948 (CDFA 2010b). California's 81,500 farms and ranches operated on 25.4 million acres and generated $34.8 billion in agricultural sales in 2009 (Figure 4). In 2002, the agriculture production and processing industries combined, directly accounted for 4.3 percent of gross state product (GSP), 3.8 percent of employment (full- and part-time workers), 2.5 percent of labor income, and 2.9 percent of value added in the state (UCAIC 2009). Cultivated land represents about 25% of state land area, of which, nearly one-third is irrigated (USDA 2009a).

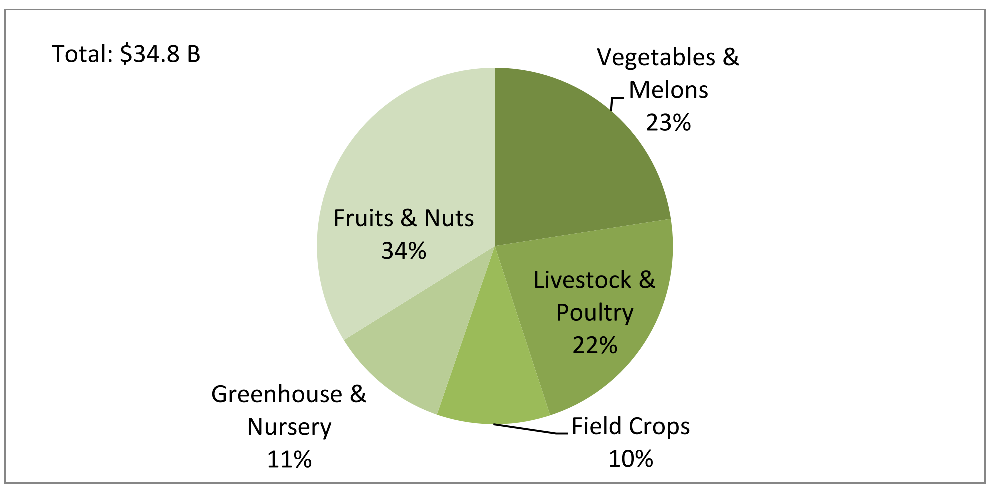

Figure 4. Distribution of California's Agricultural Sales (2009). Source: adapted from CDFA (2010a).

The state's top twenty sales commodities in 2009 (Table 1) had sales of $27.3 billion (78% of statewide agricultural sales), with eight commodities exceeding $1 billion in sales. California led the nation in the production of seventy-seven agricultural commodities, 14 of which are solely produced in California (Table 2). California's top five counties in agricultural sales are reported in Table 3 and California counties are depicted in Figure 5. Several commodities analyzed in the current paper are particularly important to the California agricultural economy. For example, the state produces nearly half of all United States grown fruits, nuts, and vegetables, with these commodities representing more than half (≈57%) of statewide sales in 2009 (Figure 4). Grapes are the state's second leading sales commodity (Table 1), constituting nearly 10% of agricultural sales, and California produces nearly 90% of all grape wine produced in the United States (Hodgen 2008). Milk and cream is the state's leading sales commodity and hay (alflalfa and other) also provides substantial value to California's agricultural economy (Table 1).[6]

Table 1. California's Top Twenty Agricultural Sales Commodities (2009). Italicized type indicates crops analyzed in the current paper. Source: adapted from CDFA (2010a).

Rank	Commodity	Value ($000)	Rank	Commodity	Value ($000)
1	*Milk and Cream*	*4,537,171*	*11*	*Hay (alfalfa and other)*	*927,496*
2	*Grapes (all)*	*3,267,848*	*12*	*Walnuts*	*738,530*
3	Nursery Products	2,848,500	*13*	*Broccoli*	*698,376*
4	*Almonds (shelled)*	*2,293,500*	14	Chickens (all)	691,518
5	*Lettuce (all)*	*1,725,799*	*15*	*Oranges (all)*	*655,820*
6	Berries	1,725,232	*16*	*Pistachio*	*592,850*
7	Cattle and Calves	1,676,373	*17*	*Carrots (all)*	*499,766*
8	*Tomatoes (all)*	*1,509,647*	*18*	*Lemons*	*364,248*
9	Flowers and Foliage	935,195	*19*	*Celery*	*349,918*
10	Rice	928,173	*20*	*Peaches*	*326,331*

Table 2. Crop and Livestock Commodities that California Leads the Nation in Production. California is the sole producer (> 99% of national production) of the commodities in bold type. Italicized type indicates crops analyzed in the current paper. Source: adapted from CDFA (2010a).

Alfalfa Hay	*Escarole/Endive*	*Melons, Cantaloupe*	***Plums, Dried***
Almonds	***Figs***	*Melons, Honeydew*	*Pluots*
Apricots	Flowers, bulbs	*Milk*	***Pomegranates***
Artichokes	Flowers, Cut	*Milk Goats*	Raspberries
Asparagus	Flowers, Potted Plants	*Nectarines*	**Rice, Sweet**
Avocados	*Garlic*	Nursery, Bedding Plants	Safflower
Beans, Dry Lima	***Grapes, Raisins***	Nursery Crops	*Seed, Alfalfa*
Bedding/Garden Plants	*Grapes, Table*	***Olives***	Seed, Bermuda Grass
Broccoli	*Grapes, Wine*	*Onions, Dry*	**Seed, Ladino Clover**
Brussels Sprouts	*Greens, Mustard*	*Onions, Green*	Seed, Vegetable and Flower
Cabbage, Chinese	Herbs	Parsley	*Spinach*
Cabbage, F.M.	*Kale*	***Peaches, Clingstone***	Strawberries
Carrots	***Kiwifruit***	*Peaches, Freestone*	*Tangelos*
Cauliflower	*Kumquats*	*Pears, Bartlett*	*Tangerines*
Celery	*Lemons*	*Peppers, Bell*	*Tomatoes, Processing*
Chicory	*Lettuce, Head*	*Persimmons*	*Vegetables, Greenhouse*
Cotton, American Pima	*Lettuce, Leaf*	Pigeons and Squabs	*Vegetables, Oriental*
Daikon	*Lettuce, Romaine*	***Pistachios***	***Walnuts***
Dates	*Limes*	*Plums*	Wild Rice
Eggplant			

Table 3. California's Top Five Counties in Agricultural Sales (2009). Italicized type indicates crops analyzed in the current paper.[6] Source: adapted from CDFA (2010a).

Rank	County	Sales ($1,000)	Leading Commodities
1	Fresno	5,372,009	*Grapes*, *Almonds*, Poultry, *Milk*, *Tomatoes*
2	Tulare	4,046,355	*Milk*, *Oranges*, Cattle and Calves, *Grapes*, *Alfalfa Hay & Silage*
3	Monterey	4,033,718	*Milk*, *Grapes*, *Citrus*, *Almonds and By-Products*, *Carrots*
4	Kern	3,606,356	*Leaf and Head Lettuce*, Strawberries, Nursery, *Broccoli*, *Grapes*
5	Merced	2,460,474	*Milk*, Chickens, *Almonds*, Cattle and Calves, *Potatoes*

Figure 5. County Boundary Map for California. This map is drawn to scale. Source: Census Finder; available at http://www.censusfinder.com/county-maps.htm.

Oregon

Oregon was the twenty-fifth ranked state in agricultural sales in 2007 (USDA 2009a) and commercially produces more than 230 agricultural commodities (Uhrich and Wentz 1999).

Oregon’s 38,800 farms and ranches cultivated 16.4 million acres and generated $4.3 billion in sales in 2010 (Figure 6). When supplementary agricultural services are included (e.g. processing, food services and drinking places, wholesale trade, retail trade, transportation and warehousing, and support services), it was estimated that Oregon agriculture is directly responsible for 12% of employment, 10.4% of GSP, and 7.1% of value added (Sorte, Lewin, and Opfer 2011). Cultivated land comprises about 27% of state land area, of which, 11% is irrigated (USDA 2009a).

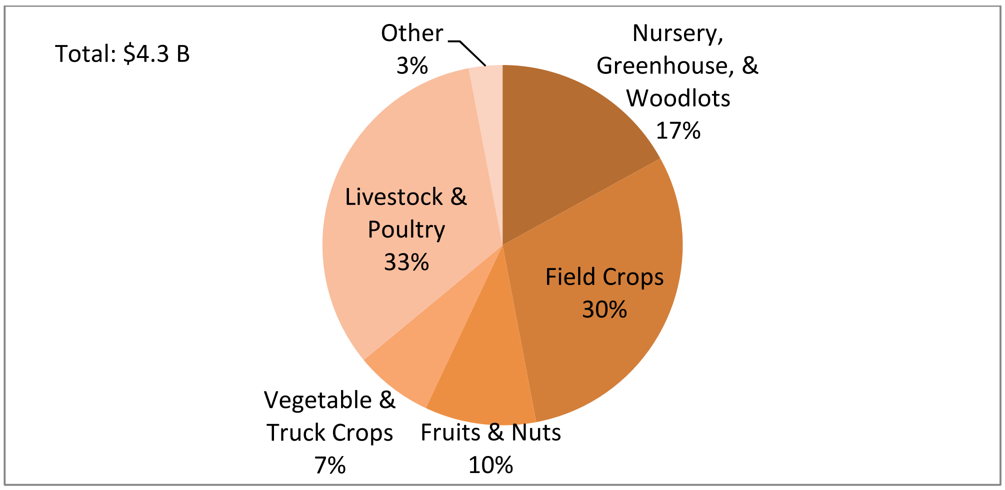

Figure 6. Distribution of Oregon’s Agricultural Sales (2010). Source: adapted from OSU (2011).

The state’s top twenty agricultural commodities in 2010 (Table 4) were valued at $3.7 billion (82% of statewide agricultural output), with 6 of these products each valued in excess of a quarter-billion dollars. The state led the nation in production of 14 commodities in 2010, 5 of which are solely produced in Oregon (Table 5). Furthermore, Oregon ranked in the top 4 in the production of 19 additional commodities (ODA 2011). Oregon’s top five counties in agricultural sales are listed in Table 6 and Oregon counties are depicted in Figure 7. All of the crops analyzed in the current paper constitute critical components of Oregon’s agricultural economy (Table 4). These crops include hay (alfalfa and other), wheat, pasture related products (i.e., milk), vegetables (i.e., potatoes and onions), and orchard and vineyard crops (i.e., cherries, pears, grapes, and hazelnuts).[7] Furthermore, Oregon is the fourth ranked state in grape wine production (Hodgen 2008).

Table 4. Oregon's Top Twenty Agricultural Sales Commodities (2010). Italicized type indicates crops analyzed in the current paper. Source: ODA (2011).

Rank	Commodity	Value ($000)	Rank	Commodity	Value ($000)
1	Nursery Products	667,040	*11*	*Pears*	*76,347*
2	Cattle and Calves	493,885	12	Corn (grain)	72,281
3	*Hay (alfalfa and other)*	*472,626*	13	Eggs	64,199
4	*Wheat (all)*	*441,620*	*14*	*Grapes*	*63,336*
5	*Milk (all)*	*415,027*	*15*	*Hazelnuts*	*59,670*
6	Grass Seed (all)	256,111	16	Blueberries	59,418
7	*Potatoes*	*141,409*	17	Crab Landings	44,904
8	*Onions*	*130,290*	18	Mint for Oil	42,839
9	Christmas Trees	99,657	19	Blackberries	37,451
10	*Cherries (all)*	*77,636*	20	Vegetable and Flower Seed	32,058

Table 5. Crop and Livestock Commodities that Oregon Leads the Nation in Production. Oregon is the sole producer (> 99% of national production) of the commodities in bold type. Italicized type indicates crops analyzed in the current paper. Source: adapted from ODA (2011)

Blackberries (all)	***Hazelnuts***	**Raspberries (black)**
Boysen and Youngberries	**Loganberries**	Red Clover Seed
Christmas Trees	Orchardgrass Seed	Ryegrass Seed
Crimson Clover	Peppermint	Sugarbeets for Seed
Fescue Seed	Potted Azaleas	

Table 6. Oregon's Top Five Counties in Agricultural Sales (2010). Italicized type indicates crops analyzed in the current paper. Source: adapted from ODA (2011) and OSU (2011).

Rank	County	Sales ($1,000)	Leading Commodities
1	Marion	512,726	*Dairy*, Eggs and Poultry, Grass and Legume Seed, Field Crops
2	Umatilla	396,721	*Grain*, *Field Crops*, *Vegetables*, Cattle and Calves
3	Morrow	395,759	*Grain*, *Hay and Forage*, Field Crops, *Vegetables*, Cattle and Calves
4	Clackamas	294,892	Eggs and Poultry, Small Fruit, *Vegetables*, Cattle and Calves
5	Malheur	273,093	Cattle and Calves, *Vegetables*, Field Crops, *Grain*, *Hay and Forage*

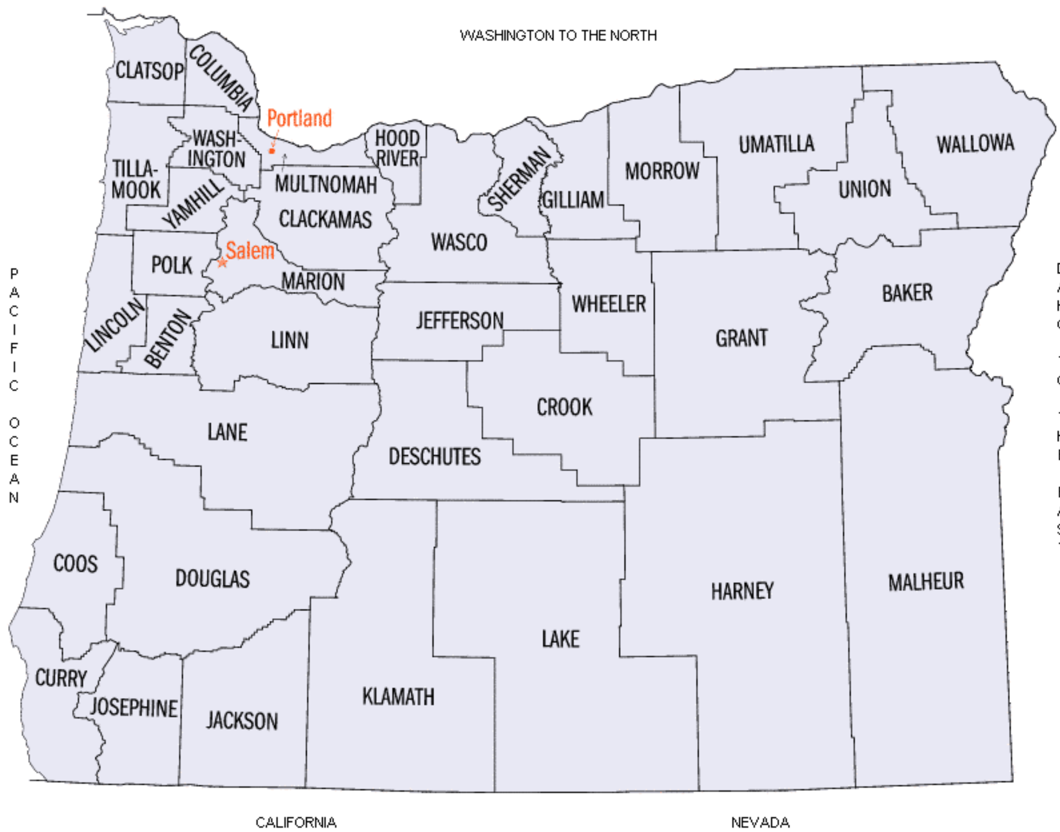

Figure 7. County Boundary Map for Oregon. This map is drawn to scale. Source: Census Finder; available at: http://www.censusfinder.com/county-maps.htm.

Washington

Washington was the sixteenth ranked state in agricultural sales in 2007 (USDA 2009a) and commercially produces some 300 agricultural commodities (WSDA 2010). The state's 39,500 farms and ranches cultivated 15 million acres and generated $7.9 billion in sales in 2010 Figure 8. Agricultural production, processing, and marketing employed 160,000 workers and accounted for $40 billion of the state's total economy in 2010, or about 12% of GSP (WSDA 2010). Cultivated land comprises about 35% of state land area, of which, 12% is irrigated (USDA 2009a).

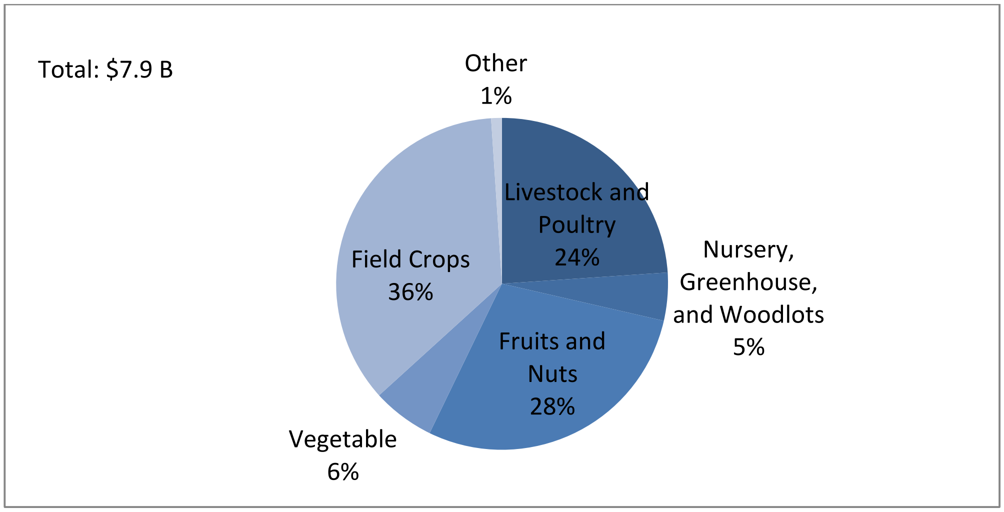

Figure 8. Distribution of Washington's Agricultural Sales (2010). Source: adapted from USDA (2011).

The state's top twenty agricultural commodities in 2010 (Table 7) were valued at $7.2 billion (91% of statewide agricultural sales) with 8 of these products each valued in excess of a quarter-billion dollars. Washington led the nation in production of 9 commodities in 2010 (Table 8) and ranked in the top 4 in production of 15 other commodities (USDA 2011). Washington's top five counties in agricultural sales are reported in Table 9 and Washington counties are delineated in Figure 9. The crops analyzed in the current paper represent 8 of Washington's top 10 agricultural sales commodities, in addition to vegetable crops such as onions and sweet corn which rank 11th and 13th, respectively (Table 7). Moreover, Washington is the third ranked state in grape wine production (Hodgen 2008). The 6 crops analyzed in the current paper are the major crops contributing to the economic value of West Coast agriculture.

Table 7. Washington's Top Twenty Agricultural Sales Commodities (2010). Italicized type indicates crops analyzed in the current paper. Source: USDA (2011).

Rank	Commodity	Value ($000)	Rank	Commodity	Value ($000)
1	*Apples*	*1,443,890*	*11*	*Onions (all)*	*168,810*
2	*Milk*	*950,061*	12	Hops	160,937
3	*Wheat*	*925,265*	*13*	*Sweet Corn (all)*	*146,656*
4	*Potatoes*	*654,456*	14	Corn for Grain	139,656
5	Cattle & Calves	568,317	15	Eggs	120,732
6	*Hay (alfalfa and other)*	*508,680*	16	Aquaculture	102,689
7	*Cherries (all)*	*367,208*	17	Corn for Silage	82,013
8	Greenhouse and Nursery	300,002	18	Broilers	61,360
9	*Grapes (all)*	*213,744*	19	Mint Oil	60,832
10	*Pears (all)*	*189,319*	20	Blueberries	54,664

Table 8. Agricultural Commodities that Washington Leads the Nation in Production. Italicized type indicates crops analyzed in the current paper. Source: USDA (2011).

Apples, All	*Grapes, Concord*	*Carrots, Processing*	Hops
Sweet Cherries	Red Raspberries	*Wrinkled Seed Peas*	Spearmint Oil
Pears, All			

Table 9. Washington's Top Five Counties in Agricultural Sales (2010). Italicized type indicates crops analyzed in the current paper. Source: WSDA (2011).

Rank	County	Sales ($1,000)	Leading Commodities
1	Yakima	1,200,000	*Apples, Milk, Hay*
2	Grant	1,190,000	*Apples,* Cattle, *Potatoes*
3	Benton	526,000	*Potatoes, Apples, Grapes*
4	Franklin	467,000	*Potatoes, Apples, Hay*
5	Adams	344,000	*Potatoes, Wheat, Apples*
5	Walla Walla	344,000	Cattle, *Wheat, Apples*

Figure 9. County Boundary Map for Washington. This map is drawn to scale. Source: Census Finder; available at: http://www.censusfinder.com/county-maps.htm

Organization of Thesis

The next chapter provides reviews of the climate change, economic, and agronomic literatures. That is followed by discussions of the conceptual framework for the empirical models and then by the econometric techniques used for estimating them. After describing the data, the econometric estimates of the behavioral equations are reported and analyzed. I then discuss implications for the design of agricultural policy and how irrigators would respond and adapt to future climate change. This paper is concluded by summarizing the results, policy implications, and insights for irrigated agriculture under climate change.

Endnotes

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[2]I 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.

[3]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 Northwest. For a definition of rule curves used by HYSSR, visit http://www.nwd-wc.usace.army.mil/PB/HYSSRM/RULECURV.pdf.

[4]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).

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

[6]Dairy production (e.g., milk and cream) often occurs on pastureland (Kendall et al. 2007) and therefore in this paper, dairy products are considered to be output from pasture operations.

[7]Potatoes are considered vegetables, as in the USDA Farm and Ranch Irrigation Survey data used in this paper (USDA 2009b).

Literature Review

Climate Change Literature

Agriculture's climate sensitivity makes it one of the most vulnerable sectors of the economy to the anticipated effects of climate change. Climate change is anticipated to accelerate the hydrological cycle and alter the yield and quality of agricultural commodities. Some crops will benefit from the forecasted changes and others will suffer, depending on the crop and the location of the production site. In addition to the concern of changing weather patterns on agricultural yield and quality, one of the most salient concerns for agricultural production in the future is intensified water scarcity.

Temperature

The preponderance of studies predict that California's average annual temperature will increase by 2-5.5°F by the mid-21st century (Cayan et al. 2009; Cayan et al. 2008; Hayhoe et al. 2004). By the end of the 21st century, average annual temperature is projected to warm by 3.5-9°F (Cayan et al. 2009; Cayan et al. 2008; Hayhoe et al. 2004). Most studies find seasonal heterogeneity in predicted temperature changes. For example, by the end of the 21st century, winter temperature increases range from 2-7°F and summer temperature increases range from 3-12°F (Cayan et al. 2008, Cayan et al. 2009).

Mote and Salathé (2010) made projections of future climate change in the Pacific Northwest (PNW) relative to baseline climate in the 1980s. Their PNW study region included Washington, Oregon, Idaho, western Montana, and a small slice of adjacent states and British Columbia. Projected increases in annual temperature are 2°F by the 2020s, 3°F by the 2040s, and 5.5°F by the 2080s. More generally, the range of warming predicted by the 2080s is 3-10.5°F, with rates ranging from 0.2-1°F per decade. Temperature is projected to increase in all seasons, with the largest increases occurring during the summer. For the 2080s, average seasonal warming projections are 5-6°F, 4-5°F, 5.5-8°F, and 4.5-6°F, for winter, spring, summer, and fall, respectively.

Precipitation

Consensus is lacking regarding future changes in average annual precipitation for the state of California. Some models predict increases of 0-20% and others predict decreases of similar magnitudes (Lobell et al. 2006). Precipitation projections are less certain than those for temperature due to intrinsic annual and decadal variability in precipitation patterns (Cayan et al. 2009). However, California is expected to maintain its Mediterranean climate that is characterized by cold-wet winters and warm-dry summers (Cayan et al. 2008, Cayan et al. 2009).

Recent research has provided insights into the spatial distribution of predicted changes in average annual precipitation in California. Cayan et al. (2009) found strong evidence of future decreases in precipitation in the Sacramento Valley and Los Angeles regions, with preliminary evidence for drying in the Shasta region. The Sacramento Valley is expected to experience diminished precipitation of up to 15% by the 2080s. The Los Angeles region is predicted to have 10-35% less precipitation by the 2080s. Under the stronger climate forcing scenario (i.e., SRES A2), there is evidence that the Shasta region will have diminished precipitation in the range of 1-23% by the 2080s. Thus, evidence suggests that climate change will decrease average annual precipitation in California, with the confidence and magnitude of these predictions increasing in more southerly regions of the state.

Modeled changes in precipitation show few clear trends for the PNW. The bulk of climate models project increases in average annual precipitation in the northern third of North America and decreases in the southern third (Christensen et al. 2007). The PNW is situated in the ambiguous transition zone between these two regions. Mote and Salathé (2010) made projections of future climate change in the PNW relative to baseline climate in the 1980s. While individual models showed changes of as much as 10% below or 20% above the 1980s mean by the 2080s, multi-model averages are virtually unchanged, showing increases in average annual precipitation of only 1-2% (Mote and Salathé 2010).

The most consistent predictions for precipitation correspond to seasonal changes (Mote and Salathé 2010). Most individual models predict decreases in summer and increases in winter precipitation. According to these results, by the 2080s, winter precipitation is projected to increase by 7.3-7.9%, while summer precipitation is projected to decrease by 11.2-14.4%. Note that a 1% change in winter precipitation is larger absolutely than a 1% change in summer precipitation. These results suggest that under future climate change, the PNW will become more arid during the summer, when agricultural water demand is greatest.

Heatwaves

Heatwaves in California are anticipated to increase in frequency, temperature, spatial extent, event duration, and seasonal duration as a result of projected warming (Hayoe et al. 2004; Gershunov and Douville 2008; Cayan et al. 2009). Event duration refers to the number of consecutive days of heatwave, while seasonal duration refers to the number of days between the beginning of the year's first and end of the year's last heatwave. Historically, California heatwaves typically occurred in July and August (Gershunov and Douville 2008). However, they are likely to begin in June and could continue to occur in September as a result of climate warming (Cayan et al. 2009). Hayhoe et al. (2004) predicted that the length of the California heatwave season would increase by 13-27 days by the 2030s and by 34-89 days by the 2080s. Cayan et al. (2009) projected that by the 2080s, the annual number of 5-day heatwaves in the Sacramento region will increase by up to 2-4.5 events. Moreover, by the 2080s, increases in all measures of heatwave duration (i.e. 1-, 2-, 3-, 4-, and 5-day events) were found for the

Sacramento region (Cayan et al. 2009). This finding is startling given the fact that each of the duration measures are mutually exclusive.

Climate warming is anticipated to increase the frequency and duration of heatwaves in Oregon and Washington. Diffenbaugh et al. (2005) examined future changes (2071-95) in extreme temperature events in the coterminous United States relative to the historic climate record (1961-85). They projected increases of approximately 10-30 heatwave days/year along the Oregon coast and Willamette Valley, 30 days/year across the Cascades and northeast regions of the state, and 40-50 days in southeast Oregon. They also investigated changes in heatwave duration, projecting increases of approximately 0-1 days/event along the coast and the Willamette Valley, 2-3 days/event in the southwest and northeast, and 4-5 days/event in the southeast region of the state.

Salathé et al. (2010) assessed the frequency of future (2030-59) heatwaves in Washington relative to historic experience (1970-99). They defined heatwaves as an episode of three or more days exceeding 90°F. Their results showed non-negative changes in heatwave frequency across the state, with the largest increases occurring in the lowlands of western Washington and in the Columbia Basin. This finding is significant because the vast majority of Oregon and Washington's top agricultural sales counties (Tables 6 and 9, respectively) are located in lowlands of the Willamette Valley (Figures 2 and 7) or the Columbia River Basin (Figures 1 and 9).

Drought

California has a long history of drought, with regularly occurring multi-year droughts (MacDonald 2007). There is a high degree of variability in annual precipitation that is projected to prevail during the next century (Cayan et al. 2009). This in tandem with the extreme seasonality of precipitation and projected decreases in summer precipitation suggest that

California will remain vulnerable to summer drought in the future (Cayan et al. 2009). Hayhoe et al. (2004) projected that the proportion of years where drought conditions are designated as "dry" or "critical" in the Sacramento River System will increase to 50-64% by the 2080s, as compared to the historical average of 32%.

A common misconception is that Oregon and Washington are regions of persistent water abundance. Portions of Oregon have exhibited multi-year droughts during years 1868-73, 1900-09, 1930-39, 1954-55, 1965-68, 1976-77, 1992-1994, and 2001-02 (Gray and Plath 1957; OEM 2012). Similarly, over the past century, Washington has experienced several multi-year drought events from 1928-32, 1992-94, and 1996-97.[1] As in California, there is a high degree of variability in annual precipitation for Oregon and Washington that is projected to prevail during the next century (Mote and Salathé 2010). This in combination with the extreme seasonality of precipitation and projected decreases in summer precipitation (Mote and Salathé 2010) suggest that Oregon and Washington will remain vulnerable to summer drought in the future. Based on simulations using the relative Standardized Precipitation Index, Chang and Jones (2010) concluded that short-term (3- and 6-month) drought in the Willamette Valley, Oregon will "increase highly" by the 2080s due to decreased summer precipitation. Historic experience and the projections of Chang and Jones (2010) suggest that summer drought risk will remain a salient concern for PNW agriculture.

Accelerating Snowmelt

The West Coast depends on snowpack, mainly in the Sierra Nevada and Cascade Mountains, that melts in the spring and summer to provide a portion of its dry season water supply. Snowpack is typically measured by April 1st snow water equivalent (April 1 SWE), an important metric used by water managers for measuring water availability and determining water allocations. Climate warming over the latter half of the 20th century caused April 1 SWE in the

Cascade and northern Sierra Nevada Mountains to diminish more rapidly than any other region in the western United States, with some areas showing declines in excess of 75% (Mote et al. 2005; Mote 2006). Numerous climate change assessments project that future climate warming will continue to accelerate West Coast snowmelt.

Projected decreases in California snowpack as a result of future climate warming are substantial. Leung et al. (2004) projected reductions in April 1 SWE of 60-70% in the northern Sierra Nevada Mountains by the 2050s. Hayhoe et al. (2004) projected statewide reductions in April 1 SWE of 26-40% by the 2030s and 29-89% by the 2080s, relative to 1961-90 snowpack levels. Cayan et al. (2008) found declines in April 1 SWE in the San Joaquin, Sacramento, and Trinity Basins, as percentages of historical averages (1961-90) that range from 12-42% by the 2050s and 32-79% by the 2080s. Losses of April 1st SWE as a result of projected climate warming will be greater at lower elevations because a "cooling buffer" exists at higher elevation (Hayhoe et al. 2004; Cayan et al. 2008). Cayan et al. (2008) projected that by the 2080s in California, April 1 SWE will decline by 60-93% at elevations of 1,000-2,000m, and by 25-79% at elevations of 2,000-3,000m. Thus, the largest reductions in California SWE are projected to occur in the lower elevation, central and northern Sierra Nevada Mountains (Cayan et al. 2008).

Projected decreases in Oregon and Washington snowpack as a result of future climate warming are comparable to that for California. Leung et al. (2004) projected that April 1 SWE in the Oregon Cascades will decline by 60-70% by the 2050s. Payne et al. (2004) predicted that relative to historic levels (1950-99), April 1 SWE west of the Cascade crest in Oregon and Washington will decrease by 36% by the 2020s, 45% by the 2050s, and 63% by the 2080s. Salathé et al. (2010) projected that relative to historic levels (1970-99), April 1 SWE in Washington will decline by 32-71% by the mid-21st century. Elsner et al. (2010) projected that relative to historic observation (1917-2006), April 1 SWE in Washington will decline by 28-30% by the 2020s, 38-46% by mid-century, and 56-70% by the 2080s. Consistent with findings for California (Hayhoe et al. 2004, Cayan et al. 2008), Elsner et al. (2010) predicted that losses of

April 1 SWE in Washington will be greatest at lower elevation. By mid-century, Elsner et al. (2010) predict losses of 49-58% at elevation <1000m, 35-43% at elevation between 1000-1999m, and 23-30% at elevation >2000m.

Glacial melt is also anticipated to accelerate with climate warming. Glacial melt, like snow melt, augments dry season streamflow and is an especially important water source during drought years for certain areas (Fountain and Tangborn 1985). For example, Oregon's Hood River Valley cultivates high-value pear, peach, and apple orchards, and is highly dependent on glacial melt during the dry season (Nolin et al. 2010). Mount Hood's glaciers have receded by as much as 61% over the 20th century (Lillquist and Walker 2006). The recession of Mount Hood's glaciers are predicted to continue under future climate warming according to findings for Mount Hood's Eliot and Coe glaciers derived from the Snowmelt Runoff Model (Nolin et al. 2010).

Runoff Timing

Warming accelerates snowmelt and can result in earlier runoff. In other words, warming causes shifts in runoff from the dry season to the wet season. Over the 20th century, California has experienced an approximate 10% decrease in the proportion of total runoff occurring in spring and thus a major decline in the dry season water supply (Moser et al. 2009). Moser et al. (2009) also finds that historic shifts in runoff have been greater for particular basins. For example, the Sacramento and San Joaquin Basins experienced 23% and 19% reductions in the proportion of total runoff occurring in spring over the same time period.

The timing of runoff in Oregon has shifted 1-3 weeks earlier over the latter half of the 20th century (Stewart, Cayan, and Dettinger 2004). In the Upper Klamath River Basin, Oregon, respective dry season (April through September) and summer (July through September) runoff declined by 16% and 38% during the period 1961-2009 (Mayer and Naman 2011). This trend was found to be closely associated with declining April 1 SWE during that period (Mayor and Naman 2010).

Runoff on the West Coast is projected to accelerate and occur earlier as a result of future warming. Leung et al. (2004) investigated mid-21st century seasonal changes in runoff for the Sacramento/San Joaquin Basin and projected declines of 7% in spring and 53% in summer, with increases of 43% in fall and 14 % in winter. Hayhoe et al. (2004) predicted that relative to the period 1961-90, runoff in the northern and southern Sierra Nevada Mountains will occur 3-24 days and 22-43 days earlier, respectively.

Leung et al. (2004) investigated mid 21st century seasonal changes in runoff for the Columbia River Basin and projected increases of 11% in winter, and declines of 9% in fall, 31% in spring, and 31% summer. In Washington, relative to years 1917-2006, wet season (October through March) runoff is projected to increase by approximately 11-12% by the 2020s, 16-20% by the 2040s, and 25-34% by the 2080s (Elsner et al. 2010). In contrast, dry season (April through September) statewide runoff is projected to decrease by approximately 16-20% by the 2020s and 23-30% by the 2040s, with mixed results (-34% to +44%) for the 2080s (Elsner et al. 2010). These findings indicate that climate warming will result in earlier runoff on the West Coast. However, because runoff dynamics are governed by the proportion of precipitation falling as rain or snow in a particular basin, the effects of climate change on runoff patterns will differ across basins.

Runoff Timing by Basin Type

Runoff dynamics are dependent on a region’s underlying geology and the relative contributions of rain and snow to annual precipitation. Elsner et al. (2010) investigated the future timing of runoff in Washington using three representative watershed types: rain-dominant (Chehalis River at Porter), transient rain-snow (Yakima River at Parker), and snow-dominant

(Columbia River at The Dalles). They found that areas dominated by rain, rather than snow, will not experience major shifts in the timing of runoff as a result of warming. This finding agrees with historic trends found for western Oregon (Jefferson et al. 2006) and projections for the western United States (Hamlet and Lettenmaier 2007) that also find that rain-dominated basins will not experience major shifts in the timing of runoff, while snow-dominated basins will. Recent mappings of PNW snow cover indicate that basins along and eastward of the Cascade crest are generally more dependent on snow than western regions (Elsner et al. 2010; Nolin and Daly 2006). Snow-dominated basins will be most susceptible to accelerating snowmelt and shifting patterns of runoff that result from climate warming.

Runoff Timing and Reservoir Management

If climate warming proceeds, dry season water scarcity will intensify on the West Coast for two reasons. Firstly, diminished dry season streamflows will reduce available water for diversion (Vano 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, thereby reducing water stored for dry-season uses (Hayhoe et al. 2004).

According to the United States Army Corps of Engineer’s Sacramento District Water Control Data System, state operators currently maintain ≈12 km^3 of total vacant space in California’s major reservoirs to provide flood protection in winter and early spring.[2] This volume is nearly equal to California’s average historical (1961-90) natural storage provided April 1 SWE (Hayhoe et al. 2004). Thus, if the recent pattern of warming continues and the rate of snowmelt continues to accelerate, reservoir managers will increasingly face tradeoffs between spilling water from reservoirs to secure winter flood protection and storing water to supply for dry season uses (Hayhoe et al. 2004). Such trade-offs will have important implications for the existing distribution of seniority in time-referenced water rights and will alter the value of rights to late season natural streamflow and the rights to stored water. It is likely that these trade-offs will be most relevant to snow-dependent basins because they are expected to experience the most profound shifts in runoff timing as a result of warming (Elsner et al. 2010; Hamlet and Lettenmaier 2007; Jefferson et al. 2006).

Water Scarcity and Agricultural Production

Climate warming is expected to diminish dry season surface water availability. Several cultural factors will also 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 streamflows for biological 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 Bureau's mission of water resource development with an explicit mandate for water resource conservation (Moore 1991). Many of these factors are expected to coalesce on the West Coast under future climate change and result in curtailed agricultural water deliveries (Vano et al. 2010) or transfers of agricultural water to higher-value uses (Purkey et al. 2008; Howitt, Medellin-Azuara, and MacEwan 2009).

The intensification of water scarcity will have important effects on the future of West Coast agricultural production. Coakley et al. (2010) concluded that the future cost of water will likely be the most limiting factor for Oregon's agricultural systems to adapt to future climate regimes. Jackson et al. (2011) anticipate that as climate change intensifies water scarcity in California's Central Valley, farmers will tend to switch to higher-value crops that provide greater income per unit of applied water. Several California climate change assessments predict that groundwater withdrawals will intensify as dry-season surface water availability declines (Joyce et al. 2009; Medellin et al. 2006). On the other hand, Purkey et al. (2008) found that farmer adaptation to climate change in terms of improvements in irrigation efficiency (e.g., adopting water-saving technologies) and shifts in cropping patterns will result in decreased agricultural groundwater withdrawals in California's Sacramento River Basin.

Economic Literature

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; Albrtecht and Ladewig 1985), water salinity (Dinar, Campbell, and Zilberman 1992; Dinar, Letey, and Knapp 1985), and whether irrigation water was discontinued long enough to affect yields (Moore, Gollehon, and Carey 1994). Economic measures of water scarcity, such as water price, are commonly included in irrigation choice models (e.g., Moore, Gollehon, and Carey 1994).

Greater water price (Moreno and Sunding 2005) or well depth (Caswell and Zilberman 1986) has been found to facilitate the adoption of water-saving technologies. Water price has also been found to reduce the quantity of agricultural water demanded (Wheeler et al. 2008; Shoengold, Sunding, and Moreno 2006; Scheierling, Loomis, and Young 2006; Moore, Gollehon, and Carey 1994; Ogg and Gollehon 1989).

Several empirical studies have shown that irrigators respond to physical water scarcity, as measured by groundwater saturation thickness, by avoiding adoption of water-saving technologies (Albrecht 1990; Albrtecht and Ladewig 1985). This finding supports Carey and Zilberman's (2002) theoretical argument 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. Carey and Zilberman (2002) concluded that "water supply or price uncertainty" creates an option value that delays and discourages investment in water-saving technologies.[3] Dinar et al. (1992) found that field share with salinity or drainage problems had a positive effect on the adoption of water-saving drip technologies. Sunding et al. (1997) showed that irrigators' primary response to short-lived water scarcity is to take land out of production.

Irrigation choice studies have modeled 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., Dinar and Yaron 1990; Ogg and Gollehon 1989). Some studies have used related temperature measures such the number of frost-free days (e.g., Moreno and Sunding 2005; Negri and Brooks 1990), growing-degree days (e.g., Negri and Brooks 1990), or cooling degree days (e.g., Moore, Gollehon, and Carey 1994) to model the effects of climate on irrigation choices. Dinar, Campbell, and Zilberman (1992) theorized that the irrigation efficiency of particular technologies is influenced by climate, which was supported by their empirical results.[4]

Negri and Brooks (1990) found that growing degree days are negatively associated with adoption of a water-saving technology (sprinkler). This result supports a finding in the agronomic literature that in warmer environments a greater proportion of water applied through sprinkler systems is lost as evaporation and in extreme conditions this technology can be inappropriate (Finkle and Nir 1983). Furthermore, it corroborates the finding that the irrigation efficiency of particular technologies is influenced by climate (Dinar, Campbell, and Zilberman 1992). Negri and Brooks (1990) also interpret this result as an indication that in cooler environments sprinklers can be used to provide frost protection. Dinar and Yaron (1990) showed that high temperature regions tended to adopt water-saving drip technologies.

Several studies have reported that drought affects irrigation choices. Wheeler et al. (2008) demonstrated that irrigators increased the quantity of water demanded in response to drought. Empirical (Schuck et al. 2005) and theoretical (Carey and Zilberman 2002) studies have found that water-saving technologies tend to be adopted in response to drought conditions. Schuck et al. (2005) demonstrated that when farmers adopted a new irrigation technology during a year of severe drought, it tended to be a water-saving irrigation technology. Carey and Zilberman (2002) argued 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. One reason for these findings is that "risk-averse farmers might consider adopting a water-efficient irrigation technology in order to reduce the production risk they face during periods of water shortage" (Koundouri, Nauges, and Tzouvelekas 2006).

Soil quality (e.g., field slope and soil permeability) has been shown to have important influences on TC (Caswell and Zilberman 1986), water demand (Shoengold, Sunding, and Moreno 2006), and irrigated land allocation (Moore, Gollehon, and Carey 1994). For example, Shoengold, Sunding, and Moreno (2006) find that the quantity of water demanded is decreasing in soil quality. Moore, Gollehon, and Carey (1994) show that farms tend to allocate more land to higher-value crops as land quality increases. However, soil quality has received special attention in the TC literature. The focus on how soil quality influences TC was prompted by the seminal work of Caswell and Zilberman (1986).

Caswell and Zilberman (1986) demonstrated theoretically that water-saving technologies, or "land quality augmenting technologies", tend to be adopted on poorer quality soils that provide low irrigation efficiencies in the absence of such technologies. Caswell and Zilberman's (1986) theoretical finding has been affirmed by numerous empirical applications (Moreno and Sunding 2005; Schuck and Green 2001; Green and Sunding 1997; Green et al. 1996). 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. Caswell and Zilberman (1986) also demonstrated 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. Thus, farms with surface water supplies are more inclined to adopt gravity technologies that require very low pressure to distribute water to crops.

One important group of findings in the technological diffusion (e.g., TC) literature concerns asset heterogeneity. Heterogeneity is a vital component of the threshold model of diffusion (Stoneman and Ireland 1986; Davies 1979). An example of asset heterogeneity is the incompatibility between certain irrigation technologies and field types or cropping patterns (Schuck and Green 2001). A defining characteristic of asset heterogeneity is that it 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). Most diffusion models of agricultural technologies focus on heterogeneity in farm size (Perrin and Winkelmann 1976) or land quality (Bellon and Taylor 1993; Schuck and Green 2001; Green and Sunding 1997; Green et al. 1996). For example, for farms with poor soil quality, production may be incompatible with gravity irrigation technologies because the quality of the soil and the irrigation technology contribute to low irrigation efficiencies (i.e. large water losses).

The technology diffusion literature has failed to identify the impact of climate heterogeneity on the diffusion of agricultural technologies, such as irrigation systems. However, crop-specific modeling provides one means for estimating how climate heterogeneity affects irrigation choices and the distributional impacts of agricultural policy. For example, in a rare study that analyzes TCs for several crops, Green and Sunding (1997) clearly demonstrated that TCs for separate crops respond differently to land quality and water price. Green and Sunding (1997) concluded that “the irrigation technology adoption decision depends critically on crop type" and "changes in water use and the impacts of water policy changes are influenced by the distribution of land allocation and land quality." Similarly, Moore, Gollehon, and Carey (1994) demonstrated that irrigated land allocations and water application rates for various crops are influenced by climate and economic water scarcity differently.

Agronomic Literature

Orchard and Vineyard: Frost Damage and Heat Stress

Orchards and vineyards cultivate perennial trees and vines, making them susceptible to damage from frost events that occur in late spring or in early fall. Late spring frosts may damage young buds and hinder yield, while early fall frosts can damage ripening fruit and product quality (Jones 2005; Evans 1999). Thus, frost events can reduce the yield and quality of orchard and vineyard crops, diminishing their marketable yields. Jones (2005) conducted an analysis of climatic change in the principal grape growing regions of the West Coast. Jones (2005) concluded that expected warming for the first half of the 21st century will not eliminate frost-risk for orchards and vineyards on the West Coast. Instead, warming will cause the length of the frost-free period to increase and therefore future frost events will pose risk to orchards and vineyards earlier in the spring and later in fall.

Above-canopy sprinkler irrigation technologies are effective tools for mitigating frost damage to orchard and vineyard crops. 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 has also been used to cool orchards which can delay bloom timing and obviate late spring frost events (Lakatos et al. 2010; Anderson et al. 1975; Alfaro et al. 1974).

Sprinkler irrigation has been shown to mitigate frost damage to fruit such as grape (Evans 1999), apple (Eccel et al. 2009; Evans 1999), plum (Lakatos et al. 2010), apricot (Hewett and Hawkins 1968), cherry, and peach (Tsipouridis, Thomidis, and Xatzicharisis 2006). Several studies have documented the effective use of sprinklers for mitigating frost damage to nuts, including almond (Micke and Kester 1998) and black walnut (Beineke 1978). The ability of sprinkler systems to mitigate crop frost damage has been 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.

Most orchard and vineyard crops are dormant during the winter, but are engaged in vegetative growth and fruit development during the spring, summer, and fall. Heat stress in orchards/vineyards, particularly during times of fruit development, can diminish the marketable yields of these commodities. Excessive heat can lead to fruit sunburn (i.e., sunscald) damage in apple (Racskó 2010; Racskó et al. 2010; Evans 2004), pomegranate (Melgarejo 2004), pear (Wand et al., 2005; Holmes, Crisera, and Brown 2009), 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 result in various physiological disorders, including diminished firmness, color, and size (Iglesias et al. 2002; Unrath 1972b; Unrath and Snead 1974). Heat stress has also caused premature abscission (i.e. fruit falling from plant) of Navel Oranges (Brewer et al. 1977). Prolonged periods with temperatures exceeding 86°F can cause heat stress in grape and induce premature véraison (i.e. transition from grape growth to ripening), grape abscission, enzyme inactivation, and less flavor development (Mullins, Bouquet, and Williams 1992).

Above-canopy sprinkler irrigation technologies are effective tools for mitigating heat stress to orchard and vineyard crops. In warm environments, sprinkler irrigation can provide evaporative cooling of crops and their surrounding microclimates. 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. Evaporative cooling can be critical to maintaining the marketable yields of crops in heat stressed environments.

Evaporative cooling provided by sprinklers has been reported for grape (Pitacco, Giulivo, and Iacono 2000; Aljibury et al. 1975; Gilbert, Meyer and Kissler 1971), apple (Evans 2004; Evans, Kroeger, and Mahan 1995; Iglesias et al. 2002; Parchomchuk and Meheriuk 1996; Unrath and Snead 1974; Unrath 1973; Unrath 1972a; Unrath 1972b), 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).

Vegetable: Frost Damage and Heat Stress

Vegetables are annual crops. There is great diversity in the growing seasons of vegetables that are cultivated on the West Coast in terms of duration and time of year, both of which depend on where the particular vegetable is grown (WSDA 2012; CDFA 2010a). Although many vegetables on the West Coast are cultivated during the summer, many other vegetables are cultivated during winter, spring, and fall. Vegetables cultivated during the winter, spring, and fall are vulnerable to damage from frost events. Frost events can damage foliage and vegetable tissue, diminishing marketable yields of the damaged crop (Dukes et al. 2012).

Above-canopy sprinkler irrigation technologies are well known for their ability to mitigate frost damage to vegetables. The process by which sprinklers mitigate frost damage to vegetables is similar to that described for orchard and vineyard crops. Sprinkler irrigation has been reported to mitigate frost damage to artichokes, lettuce (Robinson 1971), peas (Gubbels 1969; Kidder and Davis 1956), beans (Gubbels 1969; Kidder and Davis 1956), tomatoes, cucumbers, squash, peppers, broccoli (Kidder and Davis 1956), and potatoes (Wallis et al. 2011;

Gubbels 1969). Gubbels (1972) found that preventing frost damage with sprinklers extended the growing season and significantly increased the yield of peas and potato.

The growing season of many vegetables occurs during the summer. As such, numerous vegetables can become heat stressed. Excessive heat has been reported to cause sunburn damage to 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). However, vegetables are vulnerable to heat stress in ways other than sunburn.

Potato provides a useful example of how heat stress affects the yield and quality of some vegetables in ways other than sunburn. Potato is an economically important vegetable to the West Coast, particularly in Oregon (Table 4) and Washington (Table 7). The optimal temperature range for potato is 59-68°F, with an upper threshold of 77°F (Rötter and van de Geijn 1999). Marketable potato yields are 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. Third, high temperatures during tuberization have been found to contribute to lower tuber quality (Alva et al. 2002). Thus, heat stress can attenuate vegetable yield and quality, thereby reducing the marketable yields of these commodities.

Evaporative cooling provided by sprinkler irrigation has been reported for numerous vegetables. Hobbs (1973) found that for potato and bush beans, sprinkling during times of high heat provided evaporative cooling that reduced mean canopy air temperatures by 6°F. Wright, Stevens, and Brown (1981) found that sprinkling during times of high temperature cooled onion florets by up to 27°F below ambient. Cavero et al. (2009) found that sprinkling corn during times of high heat decreased crop canopy temperature by 7-11°F, which persisted for a short period following the irrigation event. Steiner, Kanemasu, and Hasza (1983) found that sprinkling reduced maximum daily leaf and canopy air temperatures of corn by 3.5°F and 5.5°F, respectively. Steiner, Kanemasu, and Hasza (1983) also found that cooling persisted throughout the day in which the irrigation event took place. Steiner, Kanemasu, and Hasza (1983) concluded that the greater frequency of irrigation applications associated with sprinkler systems may explain the reduced stress on the sprinkled plots. These findings are significant given that leaf temperature changes, as small as a few degrees, can cause important differences in the biological functions of plants (Gates 1964).

Wheat: Heat Stress

The growing seasons of wheat on the West Coast depends on the type of wheat grown.[5] Winter wheat on the West Coast is typically planted from mid-August through October and is harvested from mid-May through July. Winter wheat has vernalization (i.e., cooling) requirements which are typically satisfied during the cooler period of its growing season (Jacobsen, Jensen, and Liu 2012). Spring wheat on the West Coast usually is planted from April through May and is harvested from August to mid-September. Spring wheat does not have vernalization requirements, but due to its shorter growing season, it usually has lower yield than winter wheat. Spring wheat's growing season encompasses the warmest months of the year, making it more likely to become heat stressed.

The marketable yields of wheat are negatively impacted by heat stress. 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). Heat stress can affect the marketable yields of wheat in multiple ways. High heat accelerates wheat senescence (i.e., biological aging), which effectively reduces growing season length and therefore yields (Ferris et al. 1998). Excessive heat can reduce leaf and ear photosynthesis, which impedes grain-filling (Ferris et al. 1998). Heat stress 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). Winter wheat yields may decline if vernalization requirements are not satisfied due to high temperatures (Tubiello et al. 2002). These findings exemplify the extreme sensitivity of wheat to temperature.

Sprinkler irrigation has been shown to provide evaporative cooling of wheat. Liu and Kang (2006a) investigated the impact of sprinkler irrigation on the microclimate of a wheat field. They found that sprinkler irrigation reduced the air temperature of the sprinkled field relative to a flood irrigated field and the cooling effect persisted for 2-3 days following the irrigation event. They also demonstrated that the cooling effect was greatest when it was hot, dry, and windy with concentrated precipitation. Similar results for the effects of sprinkler irrigation on the microclimate of a wheat field were found by Liu and Kang (2006b).

The agronomic literature does not identify whether wheat is vulnerable to frost damage. As a result, there is no indication in the literature that particular irrigation technologies are used to mitigate frost damage to wheat.

Alfalfa: Heat Stress

Alfalfa, also known as lucerne, is a perennial leguminous plant. It is the most important hay plant in North America.[6] The active growing season of alfalfa depends on the location of the production site. In Washington, alfalfa's active growing season extends from mid-February through November. California's warmer climate provides an extended growing season for alfalfa. In California's warmest regions, such as the Imperial Valley, the growing season extends year-round (Putnam et al. 2001). In warmer environments, the longer growing season results in higher yield and absolute water use (Putnam et al. 2001; 2000). Because alfalfa's growing season extends through the summer, it is often subjected to high temperatures that can adversely affect yield and quality.

The agronomic literature has identified specific temperature thresholds under which alfalfa becomes heat stressed. 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 plant cells from severe damage and enable survival (Königshofer and Lechner 2002). These findings communicate the sensitivity of alfalfa to high temperature.

Evaporative cooling by sprinkler irrigation has effectively regulated the temperature of alfalfa in hot environments. In California's Imperial Valley, the temperature of alfalfa plants was kept below 93°F while sprinklers were operating (Robinson 1970). Furthermore, plant temperature was reduced as much as 38°F during August. Thus, the findings of Robinson (1970) suggest that evaporative cooling by sprinkler irrigation maintained alfalfa plant temperature below the critical threshold necessary for survival.

There is a paucity of literature conveying whether alfalfa is vulnerable to frost damage. Likewise, there is no indication in the literature that particular irrigation technologies are used to mitigate frost damage to alfalfa.

Hay

There is a dearth of literature documenting the susceptibility of hay to frost damage or heat stress, and therefore there is no evidence that particular irrigation technologies are used to mitigate these climatic stressors.

Pasture

There is a lack of literature documenting the vulnerability of pasture to heat stress or frost damage. However, the agronomic literature does report that in the hot and humid southeastern

United States, pastured livestock such as dairy cattle are vulnerable to heat stress (Kendall et al. 2007; Smith et al. 2006). In the 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). Outdoor cooling ponds are another method used to alleviate heat stress in pastured dairy cows (Fike et al. 2002). Nonetheless, the literature does not indicate that certain irrigation technologies are used in the pasture to cool livestock.

Endnotes

[1]The Washington Military Department's Emergency Management Division provides a discussion of drought history in Washington at http://www.emd.wa.gov/hazards/haz_drought.shtml.

[2]The United States Army Corps of Engineer's Sacramento District Water Control Data System can be accessed at www.spkwc.usace.army.mil.

[3]According to Carey and Zilberman (2002), with uncertainty in 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.

[4]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.

[5]The Minnesota Association of Wheat Growers provides information on planting and harvest dates for United States grown wheat at http://www.smallgrains.org/WHFACTS/uswinwhe.htm.

[6]The National Science Foundation's Center for Integrated Pest Management discusses alfalfa and profiles its use in Washington at http://www.ipmcenters.org/cropprofiles/docs/WAalfalfa.pdf.

Materials and Methods

Empirical Models

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 expected 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 for the six major crops. These procedures result in thirteen 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 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 are 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. Population density is an indicator of water scarcity because 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). Two interaction variables are included in **S** to control for the effects of institutional arrangements (Moore 1999) and having a surface water supply on surface water price responsiveness (Green and Sunding 1997). Likewise, an interaction variable is included in **S** to control for the effect of having a groundwater supply on well depth responsiveness (Caswell and Zilberman 1986). 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 equations. Annual maximum temperature, annual precipitation, and their squares are included in all equations as well. For the crop-specific TC and AR equations, a variable indicating whether the farm used irrigation to mitigate heat stress is included in the vector **C** for orchard/vineyard, vegetable, wheat, and alfalfa. 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.

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, whether the farm is only supplied with surface water, and whether the farm is only supplied with groundwater are included in all estimated equations. Several studies demonstrate that irrigated land allocations for various crops are influenced by economic water scarcity and climate differently (Moore, Gollehon, and Carey 1994; Adusumilli, Rister, and Lacewell 2011). Thus, PI is conditioned on crop choice by including binary variables in the vector **G** that indicate the crop portfolio of the farm. According to Dan O'Brien (personal communication), the manager of the Greenberry Irrigation District south of Corvallis, Oregon, irrigation is commonly used in livestock operations to dispose of livestock waste. Therefore, a variable indicating if the farm used this practice is included in the vector **G** for the PI and pasture TC and AR equations.

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). I 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.[1] 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.

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

$$\mathbf{PI}_j = h(\mathbf{S}, \mathbf{C}, \mathbf{G}, \mathbf{I}, \mathbf{D}); \tag{1}$$

$$\mathbf{TC}_{jk} = m(\mathbf{S}, \mathbf{C}, \mathbf{G}, \mathbf{I}, \mathbf{D}), \tag{2}$$

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

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

and k = orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture, respectively. Equations (1), (2), and (3) are estimated using agricultural production data for the states of California, Oregon, and Washington. Next, the econometric estimation approaches are discussed.

Econometric Estimation

PI is the proportion of cropland irrigated.[2] There are a non-trivial number of irrigators that 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.

Discrete irrigation technology choices are analyzed 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 (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 Role of Prices

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, which 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 controls 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. Similarly, irrigators with only access to surface water were assumed to have well depth equal to zero. There are two variables in every estimated equation which controls for this convention: (1) a variable indicating if the farm only irrigated with groundwater supplies, and (2) that groundwater supply variable interacted with well depth. 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.

Robustness Tests

Functional Form

Logit models are used for TC, and no alternative functional forms were tested. Logit models are the most common method for modeling discrete choices, such as TC (e.g., Schuck and Green 2001; Green and Sunding 1997; Green et al. 1996; Negri and Brooks 1990). However, other procedures are available. For example, Nieswiadomy (1988) estimated irrigation technology demand functions using duality theory and a trans-log cost function. Because the PI data is censored at 1, the Tobit model was used for PI, and no alternative functional forms were tested.

AR models were robust to alternate functional forms. OLS linear, linear-log, log-linear, and log-log functional forms were tested. Each AR model performed similarly across functional forms, but slight improvements in model fit were achieved through the use of particular functional forms for certain crops. Linear functional forms are used for all AR models except for orchard/vineyard, which uses a log-linear form.

There are two reasons why it is appropriate to use the log-linear functional form for the orchard/vineyard AR model. First, AR has a high degree of variation because orchards tend to consume substantially more water than vineyards (Blaney 1957; USDA 1982). Because most observations for orchard/vineyard AR are above 1, taking the logarithm of orchard/vineyard AR tightens this variation, resulting in a better fit between AR and the explanatory data. Second, water demand for different crops responds differently to the explanatory variables (Moore, Gollehon, and Carey 1994; Adusumilli, Rister and Lacewell 2011). This suggests that modeling the same process for different crops may be best achieved through different functional forms.

Model Specification

Tests revealed that PI, TC, and AR models are robust to alternate specifications. A similar set of independent variables are used across all estimated equations. This approach enhances comparability across models. Because of the stability of each model to alternative specifications it was possible to use a similar set of independent variables across models without adversely affecting the results of any individual model. The similarity of independent variables used across models is a testament to the robustness of the PI, TC, and AR models to alternate specifications.

Outlying Data

A small number of outlying observations were removed from the data. Observations in the orchard/vineyard (n=5) and vegetable (n=2) categories that had AR greater than 7 acre-feet were removed from all models. Removing these observations did not perturb the signs of the estimated coefficients, but they did improve the model fit for orchard/vineyard and vegetable AR equations. There is an agronomic justification for only removing outliers from the orchard/vineyard and vegetable models. Orchard/vineyard and vegetable are the most diverse crop categories analyzed in this paper. Observations for the orchard/vineyard and vegetable categories include numerous crop species (USDA 2009b), each of which is likely to have several commercially cultivated varieties (e.g., FAO 2008). None of the other crop categories have this magnitude of diversity.

Removing outlying data from highly diverse crop categories may purge observations that correspond to ‘outlying crop species or varieties’ that have systematic differences in irrigation practice. For example, orchards tend to consume notably more water than vineyards (Blaney 1957; USDA 1982), and the USDA (1982) has reported that walnuts and peaches consume about three-halves the water of citrus trees (lemons and oranges). Therefore, the procedure used for removing outlying data is justified.

Data

Cross-sectional micro data 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.[3] 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.[4] The data are evenly distributed across the tri-state study region. California houses 40% of irrigators, while Oregon and Washington house 29% and 31%, respectively.

Farms cultivating only one of the six major crops represent 46% of irrigators, while multicrop production enterprises comprise the remaining 54%. Mean cropland proportion irrigated is 79% (Table 10). 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 (Table 10). Sprinkler irrigation is more frequently used for wheat and alfalfa than for hay and pasture (Table 10). Orchard/vineyard and vegetable TC is dominated by drip and sprinkler technologies, respectively. Farms that solely irrigate with surface water comprise 47% of irrigators, while 20% of irrigators solely use groundwater (Table 11). Thus, 80% of irrigators receive at least some water from surface supplies.

Irrigators that experienced discontinued irrigation represent 17% of irrigators (Table 11). These irrigators had water supplies discontinued for a long enough period to affect yields. 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. Moore, Gollehon, and Carey (1994) also use FRIS and this variable in their investigation of multicrop production relationships in Western irrigated agriculture.

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 observations at 669 and 723 weather stations, respectively, across the 111 counties in the tri-state study region

(Figures 5, 7, and 9). Mean maximum temperature for the tri-state study area is about 66°F and mean annual precipitation is approximately 19 inches (Table 11). 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".[5] Drought counties contain 64% of irrigators (Table 11). The land quality variable was obtained 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. County-level population density (2007) was assembled from population and land area data at the United States Census Bureau.

Table 10. Descriptive Statistics for Dependent Variables

Variable (units)	Mean	Std. Dev.	Min.	Max.
Proportion Irrigated (proportion)	0.79	0.32	9.09E–5	1.00
Water Application Rates (acre-feet)				
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
Variable (units)	% Gravity	% Sprinkler	% Drip	
Multinomial Technology Choice (0,1,2)[a,b]				
Orchard/vineyard	15	30	55	
Vegetable	21	62	17	
Binomial Technology Choice (0,1)[a,b]				
Wheat	39	61	—	
Alfalfa	37	63	—	
Hay	56	44	—	
Pasture	53	47	—	

[a]The base case (0) are gravity technologies.
[b]Binary TC variables also enter the AR models as independent variables.

Table 11. 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	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)
Ground supply	0.20	0.40	Farm receives all (>99%) water from ground 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)
Waste disposal	0.03	0.18	Farm uses irrigation to dispose of livestock waste (0,1)
Institutional			
Federal supply[c]	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 with access to groundwater. Farms without access to groundwater are assumed to have well depth equal to zero.
[c]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. The U.S. Bureau of Reclamation is, by far, the largest irrigation water supply organization (Moore 1991).

Endnotes

[1]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.

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

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

[4]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”.

[5]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, the identified drought counties are satisfactory for denoting drought prone regions on the West Coast.

Estimation Results

Cropland Proportion Irrigated

Estimated marginal effects and estimation statistics for the Tobit PI model are presented in Table 12. Complete coefficient estimation results for PI are included in Table A.1 (Appendix). The Tobit marginal effects are calculated by multiplying the marginal effect of the independent variable on the latent variable by the probability that the independent variable is uncensored (Maddala 1987). The McFadden R^2 is calculated as $R^2 = 1 - L_\Omega/L_\Phi$, where L_Ω is the unrestricted maximum log-likelihood and L_Φ 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 squared correlation is calculated by squaring the correlation between the observed and predicted values of PI (Dinar, Campbell, and Zilberman 1992). The log-likelihood ratio test indicates that the model performs well. More than two-thirds of the marginal effects in Table 12 are significant at the 10% level or better and more than one-third are significant at the 1% level or better.

The results indicate that PI is highly dependent on water scarcity. For irrigators with federally supplied surface water, PI tends to be greater and responsive to surface water price. PI for irrigators with federal surface water supplies is likely greater because mean surface water prices for this group are 29% lower than for all irrigators (Table 13) and irrigators typically respond to lower water prices by increasing the quantity of water demanded (Schoengold, Sunding, and Moreno 2006). Thus, the current results corroborate the finding that federal water suppliers, such as the Bureau, subsidize agricultural water (Moore 1999).[1] Because irrigators with federally provided surface water tend to have higher PI, the marginal benefit of PI for these irrigators is likely to be lower, causing the demand curve for PI to be flatter and more responsive to increasing water prices. 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 negatively associated with PI also. This result suggests that the intense competition for water in more densely populated areas (Kummu et al. 2010) causes PI to decline.

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. Drought is positively related with PI, which suggests that irrigation is necessary to satisfy crop water needs in arid conditions. Similarly, this result supports the finding that agricultural water demand is greater under drought conditions (Wheeler 2008).

The statistical results show that geographic factors are important determinants of PI. The results show that irrigators with only a surface water supply tend to have greater PI. Table 13 displays descriptive statistics for surface water prices by institutional provider and physical source. Mean surface water prices for irrigators with only surface supplies are 34% lower than 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 this group of irrigators tend to have higher PI. 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 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).[2] 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.[3]

Results demonstrate that farmers generally increase the extent of irrigation when there are relatively few use restrictions on the land. This suggests that land quality must be above some minimum level for irrigators to invest in irrigation infrastructure. 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, if the farm uses irrigation to dispose of livestock waste, PI tends to be greater. According to Dan O'Brien (personal communication), the manager of the Greenberry Irrigation District south of Corvallis, Oregon, pastures with 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 provide 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 small 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 (0.62). Clawson (1963) reported that farmers tend to slowly reduce their extent of farm production as they approach retirement. That finding helps explain the negative effect of farm experience on PI.

Table 12. Tobit Marginal Effects and Estimation Statistics of PI

Variable	dF/dx	Asymp. z-stat.
Surface water price	−1.3E−5	−0.65
Surface water price × Federal supply	−0.0004**	−2.36
Surface water price × Surface supply	−0.0001	−1.31
Well depth	1.3E−5	0.68
Well depth × Ground supply	1.4E−5	0.37
Discontinued irrigation	[−0.0222]**	−2.11
Population density	−0.0065***	−3.34
Drought region	[0.0261]*	1.81
Temperature	−0.0240**	−2.19
Temperature squared	0.0002***	2.73
Precipitation	0.0028**	2.39
Precipitation squared	−3.7E−5**	−2.49
Federal supply	[0.0795]***	7.26
Surface supply	[0.0231]**	1.96
Ground supply	[0.0206]	1.21
Land quality	0.1579***	5.84
Farm-scale	−0.0007***	−5.98
Orchard/vineyard[a]	[0.0572]***	5.59
Vegetable	[0.0548]***	5.66
Wheat	[0.0231]**	2.45
Hay	[−0.0282]*	−2.98
Pasture	[−0.0239]**	−2.44
Waste disposal	[0.0749]***	3.71
Tenure	[0.0060]	0.69
Internet	[−0.0112]	−1.03
Farm occupation	[−0.0021]	−0.19
Farm experience	−0.0013***	−4.80
Intercept	0.8644	2.18
Estimation statistics		
Observations		1,461
Uncensored observations		791
Right-censored observations at PI=1		670
McFadden R^2		0.23
Squared correlation		0.29
LR chi^2 (df=27)		472.39

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 13. Descriptive Statistics of Surface Water Prices by Provider and Source

Provider and Source	Mean	Std. Dev.	Min.	Max.
Federal surface supply	37.53	44.43	0	384.62
Surface supply only	34.97	141.80	0	3600.00
All irrigators[a]	52.97	206.29	0	4891.59

Note: All surface water prices are expressed in dollars ($).
[a]The category "all irrigators" includes 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.

Crop-specific Technology Choice

Estimated marginal effects and estimation statistics from the multinomial and binomial logit crop-specific TC models are reported in Table 14 and Table 15, respectively. The estimated marginal effects will allow comparison of choices across crop types and technologies. Complete coefficient estimation results for the multinomial and binomial cases are presented in Table A.2 and Table A.3, respectively (Appendix). The log-likelihood ratio test indicates that all TC equations perform well. By comparing the probabilities of choice (Table 14) to the observed TCs (Table 10), it is shown that the multinomial equations correctly predict that orchard/vineyard TC is dominated by the choice of drip, while vegetable TC is dominated by the choice of sprinkler technologies. The hay equation (Table 15) substantially under predicts the probability of choosing sprinklers when compared to hay irrigators' observed TCs (Table 10). Thus, there is some evidence that key variables are omitted from the hay TC equation.

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 avoidance 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 and alfalfa equations show that when irrigation is used to mitigate heat stress, sprinklers are more likely to be adopted than gravity technologies.

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 avoidance 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. The hay and pasture equations suggests that below a temperature threshold of 63°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 heat stress on orchard/vineyard, wheat, and alfalfa TC support agronomic literature reporting the effectiveness of sprinklers for mitigating heat stress damage to these crops. However, vegetable TC is not found to be impacted by heat stress or temperature despite agronomic evidence to the contrary (see “Agronomic Literature” section). Therefore, the estimated results may reflect that there are cool season and warm season vegetables (WSDA 2012; CDFA 2010a) 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 and flexibility 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. 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 the effect of precipitation on the probability of adopting sprinklers reaches a minimum at 50 inches of precipitation. This suggests that in dryer environments that are below the threshold level of precipitation, higher precipitation increases soil moisture and lessens incentives to adopt the water-saving technology. In wetter environments above the threshold level of precipitation, wheat irrigators are more inclined to adopt sprinklers that can systematically manage soil moisture in response to heavier or more frequent precipitation events. One reason why wheat irrigators tend to avoid 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 10).

Table 14. Elasticities, Probabilities, and Estimation Statistics of Multinomial Logit TCs

	Orchard/vineyard			Vegetable		
Variable	Gravity	Sprinkler	Drip	Gravity	Sprinkler	Drip
Surface water price	3.3E−5	−0.0007*	0.0007*	−0.0018*	0.0018*	9.1E−6
	(0.96)	(−1.66)	(1.68)	(−1.76)	(1.77)	(0.04)
Surface water price × Federal supply	−0.0003	−0.0008	0.0011	0.0008	−0.0007	−0.0001
	(−0.78)	(−0.86)	(1.18)	(0.80)	(−0.66)	(−0.25)
Surface water price × Surface supply	−0.0007*	0.0010**	−0.0004	−3.1E−5	−0.0004	0.0005
	(−1.94)	(2.33)	(−0.74)	(−0.03)	(−0.37)	(0.95)
Well depth	−5.0E−5	−0.0001	0.0001	−0.0002**	0.0003**	−3.6E−5
	(−1.17)	(−0.70)	(1.14)	(−1.99)	(2.04)	(−0.67)
Well depth × Ground supply	0.0001	−2.9E−5	−0.0001	0.0003	−0.0004	0.0001
	(1.23)	(−0.12)	(−0.24)	(0.97)	(−1.15)	(0.62)
Discontinued irrigation	[0.0436]	[−0.0556]	[0.0120]	[0.0925]	[−0.1247]	[0.0322]
	(1.42)	(−0.81)	(0.17)	(1.23)	(−1.46)	(0.78)
Population density	−0.0004	−0.0014	0.0018	0.0600**	−0.0759**	0.0159
	(−0.22)	(−0.13)	(0.17)	(2.20)	(−2.19)	(0.88)
Drought region	[−0.2002]	[0.1194]	[−0.0992]	[−0.1085]	[0.1931]*	[−0.0846]
	(−0.90)	(1.45)	(−1.18)	(−1.23)	(1.79)	(−1.22)
Frost mitigation	[−0.0375]**	[0.0906]*	[−0.0531]	[−0.1323]***	[0.1764]***	[−0.0441]
	(−2.02)	(1.70)	(−0.96)	(−3.35)	(3.74)	(−1.46)
Heat stress mitigation	[0.0174]	[0.1628]**	[−0.1802]**	[0.0818]	[−0.0791]	[−0.0027]
	(0.64)	(2.25)	(−2.46)	(0.97)	(−0.86)	(−0.07)
Temperature	0.0907	−0.0706	−0.0201	−0.0637	0.0341	0.0296
	(1.61)	(−0.78)	(−0.20)	(−1.00)	(0.42)	(0.59)
Temperature squared	−0.0006	0.0004	0.0002	0.0005	−0.0004	−0.0002
	(−1.54)	(0.61)	(0.31)	(1.26)	(−0.72)	(−0.45)
Precipitation	0.0067*	0.0060	−0.0127	0.0230***	−0.0362***	0.0133**
	(1.72)	(0.75)	(−1.52)	(2.89)	(−3.59)	(2.45)
Precipitation squared	−0.0001*	−2.2E−5	0.0001	−0.0004***	0.0007***	−0.0003***
	(−1.69)	(−0.20)	(1.18)	(−3.37)	(4.53)	(−3.15)
Federal supply	[−0.0071]	[0.0268]	[−0.0197]	[0.0923]	[−0.0788]	[−0.0135]
	(−0.31)	(0.35)	(−0.25)	(1.35)	(−0.97)	(−0.36)
Surface supply	[0.0458]	[0.0415]	[−0.0873]	[0.0060]	[0.0099]	[−0.0159]
	(1.29)	(0.54)	(−1.10)	(0.09)	(0.12)	(−0.34)
Ground supply	[−0.0171]	[−0.0163]	[0.0334]	[−0.1599]***	[0.2073]***	[−0.0474]
	(−0.73)	(−0.16)	(0.33)	(−2.81)	(3.00)	(−1.20)
Land quality	−0.0345	0.1744	−0.1400	0.1130	−0.1355	0.0225
	(−0.67)	(0.85)	(−0.67)	(0.71)	(−0.69)	(0.22)
Farm-scale	−0.0095***	−0.0095	0.0190**	−0.0061	0.0027	0.0034
	(−3.49)	(−1.17)	(2.30)	(−1.28)	(0.50)	(1.35)
Crop diversity	0.0137*	0.0134	−0.0271	0.0260	0.0032	−0.0292
	(1.78)	(0.54)	(−1.05)	(1.34)	(0.11)	(−1.50)
Tenure	[0.0048]	[0.0623]	[−0.0671]	[−0.0125]	[−0.0662]	[0.0787]
	(0.31)	(1.16)	(−1.23)	(−0.25)	(−0.89)	(1.44)
Internet	[−0.0329]	[−0.2103]**	[0.2431]***	[−0.1230]	[0.1236]	[−0.0006]
	(−1.17)	(−2.32)	(2.75)	(−1.20)	(1.12)	(−0.02)
Farm occupation	[0.0198]	[0.0995]**	[−0.1194]**	[0.0723]	[−0.1211]**	[0.0488]
	(1.29)	(1.97)	(−2.28)	(1.39)	(−1.99)	(1.56)
Farm experience	0.0014**	0.0004	−0.0018	0.0016	−0.0024	0.0008
	(2.36)	(0.24)	(−1.02)	(1.09)	(−1.31)	(0.86)
Probability of choice	0.05	0.25	0.70	0.14	0.80	0.06
Estimation statistics						
Observations		485			386	
McFadden R^2		0.26			0.36	
LR chi^2 (df=48)		250.91			261.90	
Correct prediction		67%			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 15. Elasticities, Probabilities, and Estimation Statistics of Binomial Logit TCs

	Wheat	Alfalfa	Hay	Pasture
Variable	Sprinkler	Sprinkler	Sprinkler	Sprinkler
Surface water price	0.0007	0.0001	−2.3E−5	0.0008
	(0.68)	(0.18)	(−0.05)	(0.70)
Surface water price	0.0037**	0.0015	0.0002	−0.0014
× Federal supply	(2.02)	(0.54)	(0.25)	(−0.88)
Surface water price	−0.0059**	−0.0007	0.0001	0.0008
× Surface supply	(−2.38)	(−0.31)	(0.07)	(0.51)
Well depth	0.0004**	0.0001	0.0002	0.0001
	(1.99)	(0.50)	(1.54)	(0.32)
Well depth	−0.0006	−0.0002	0.0002	0.00011
× Ground supply	(−1.18)	(−0.53)	(0.69)	(0.18)
Discontinued irrigation	[−0.1560]*	[−0.1276]*	[−0.0408]	[−0.1201]
	(−1.76)	(−1.79)	(−1.25)	(−1.37)
Population density	0.0086	0.0207	0.0065	−0.0047
	(0.17)	(0.70)	(0.50)	(−0.11)
Drought region	[0.1328]	[0.0933]	[0.0660]	[0.2940]*
	(1.00)	(0.80)	(1.22)	(2.04)
Heat stress mitigation	[0.2185]*	[0.4948]***	—	—
	(1.72)	(5.90)		
Temperature	0.4895***	0.4450**	0.5007***	1.6543***
	(3.12)	(2.33)	(6.82)	(7.34)
Temperature squared	−0.0043***	−0.0040***	−0.0040***	−0.0129***
	(−3.72)	(−2.83)	(−7.12)	(−7.31)
Precipitation	−0.0396***	0.0044	0.0095**	0.0240*
	(−2.88)	(0.32)	(2.01)	(1.82)
Precipitation squared	0.0004**	3.1E−5	−0.0001	−0.0001
	(2.40)	(0.14)	(−0.87)	(−0.81)
Federal supply	[−0.3064]***	[0.0504]	[0.0334]	[0.0785]
	(−3.14)	(0.47)	(0.70)	(0.79)
Surface supply	[−0.0365]	[−0.0760]	[−0.0181]	[−0.0803]
	(−0.28)	(−0.71)	(−0.35)	(−0.71)
Ground supply	[0.4604]***	[0.3705]***	[0.1437]	[0.1638]
	(2.98)	(2.70)	(1.01)	(0.87)
Land quality	0.0109	0.9480***	0.4707***	2.3452***
	(0.04)	(3.57)	(3.53)	(6.58)
Farm-scale	−0.0010	−0.0002	−0.0002	−0.0077*
	(−0.21)	(−0.17)	(−0.78)	(−1.70)
Crop diversity	0.0340	0.0007	0.0702***	−0.0066
	(0.93)	(0.02)	(3.00)	(−0.17)
Waste disposal	—	—	—	[0.5416]***
				(8.59)
Tenure	[0.0623]	[−0.0881]	[0.0166]	[−0.0072]
	(0.68)	(−1.24)	(0.51)	(−0.09)
Internet	[0.1433]	[0.1700]**	[−0.0173]	[−0.0555]
	(1.57)	(2.18)	(−0.39)	(−0.56)
Farm occupation	[−0.0836]	[0.0402]	[−0.0563]	[0.0038]
	(−0.57)	(0.38)	(−0.98)	(0.04)
Farm experience	−0.0017	−0.0034	−0.0022*	−0.0044*
	(−0.64)	(−1.51)	(−1.95)	(−1.66)
Probability of choice	0.47	0.49	0.13	0.43
Estimation statistics				
Observations	501	651	416	356
McFadden R^2	0.48	0.53	0.33	0.38
LR chi^2 (df)	321.34 (23)	456.94 (23)	188.13 (22)	186.40 (23)
Correct prediction	87%	88%	79%	80%

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.

The vegetable equations show that the effect of precipitation on the probability of adopting gravity and drip reach their respective maximums at 29 and 22 inches of precipitation. The effect of precipitation on the probability of adopting sprinklers reaches a minimum at 26 inches of precipitation. Thus, gravity, sprinkler, and drip equations reach their thresholds at approximately 25 inches of precipitation. 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 precipitation threshold will facilitate avoidance 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).[4] 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 show that alfalfa is the only major West Coast crop with TCs that are not influenced by precipitation. One reason for this finding is that alfalfa crops typically have deeper root zones than all other major West Coast crops, which likely make it less vulnerable to variations in soil moisture caused by under- and over-irrigation. Putnam (2001) reported that alfalfa roots are commonly 15 feet or deeper. Thus, alfalfa is likely to be less dependent on particular irrigation technologies for the systematic management of soil moisture.

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 empirical (Schuck et al. 2005) and theoretical findings (Carey and Zilberman 2002) findings that water-saving technologies tend to be adopted in response to drought conditions. 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 for orchard/vineyard.

Statistical results communicate the importance of economic and physical water scarcity to TC. It is found that surface water price facilitates adoption of sprinklers and avoidance of gravity technologies for vegetable. For wheat growers with federal surface water supplies, surface water price encourages adoption of the water-saving technology. 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. The orchard/vineyard equations reveal that if the farm only has surface water supplies, surface water price induces adoption of sprinklers and avoidance of gravity technologies. However, the counter intuitive result is found 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 avoidance of gravity technologies for vegetable and wheat 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 and alfalfa equations show that the discontinuance of irrigation water encourages avoidance of sprinklers and adoption of gravity technology. 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.[5] Empirical studies have shown that farms with less groundwater saturation thickness (i.e., groundwater availability) tend to avoid adoption of water-saving technologies (Albrecht 1990; Albrecht and Ladewig 1985). Thus, the current empirical results affirm the theoretical conclusion of Carey and Zilberman (2002) that "water supply or price uncertainty" creates an option value that delays and discourages investment in water-saving technologies. One reason why the results show that vegetable irrigators tend to avoid 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 mean surface water prices that are 29% lower than for all irrigators (Table 13). 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 lack of 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 indicate that irrigators of these crops have a strong propensity to adopt the water-saving technology when land quality is better. 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.

The results show that all crops are inclined to adopt a water-saving technology if the farm only has a groundwater supply, with the effects for vegetable, wheat, and alfalfa being significant. The results also show that all crops are more likely to adopt gravity technologies when the farm only has a surface water supply, but none of these results are significant. These results corroborate Caswell and Zilberman’s (1986) theoretical argument 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. Thus, farms with surface water supplies are more inclined to adopt gravity technologies that require very low pressure to distribute water to crops.

TC is affected by farm-scale according to the statistical results. The statistical results show that as farm-scale increases, orchard/vineyard irrigators are inclined to avoid gravity technologies and to adopt drip technologies, while vegetable irrigators are inclined to adopt sprinkler and drip technologies. However, only the results for orchard/vineyard are significant.

These results support previous findings that farm scale-economies increase incentives to adopt water-saving technologies (Green and Sunding 1997; Green et al. 1996). Results indicate that wheat, alfalfa, hay, and pasture irrigators are less likely to adopt the water-saving technology as farm-scale increases. However, only the result for pasture is significant. This result supports the hypothesis of an "economies of smallness" in agricultural technology adoption, which states that a "small land area provides an incentive to adopt high-payoff, input intensive innovations" (Dinar, Yaron, and Voet 1992). Descriptive statistics of land allocation (Table 16) also indicate that larger farm-scales are important for orchard/vineyard, and least important to pasture. Therefore, the results suggest that on the West Coast, economies of smallness only exist for lower-value crops.

Table 16. 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	1,323	2,586
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.

Crop diversity is found to affect high- and low-value crops differently. The orchard/vineyard equation shows 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 10). These results confirm my 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.

The results show that when farms with pasture use irrigation to dispose of livestock waste, irrigators are highly inclined to adopt sprinklers. Sprinklers are likely used to dispose of livestock waste because, relative to gravity technologies, sprinklers allow greater control and flexibility over the timing and spatial distribution of irrigation water (Shock, Pereira, and Eldredge 2007; Negri and Brooks 1990; Finkel and Nir 1983). Furthermore, sprinklers are likely used to dispose of livestock waste because, relative to drip technologies, sprinklers can provide heavy enough flows to transport waste material.

Demographic characteristics are found to be more important for TC than for PI or AR. 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 avoided 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).

Results show that occupation impacts TC for the highest-value crops. When farming is the primary occupation of the farm operator, orchard/vineyard irrigators tend to adopt sprinklers and abandon drip technologies, while vegetable irrigators tend to avoid sprinkler technologies. Reasoning for the estimated effects of occupation on TC is unclear. However, several studies have documented the importance of occupation to agricultural technology adoption for producers of high-value fruits and vegetables (Fernandez-Cornejo 1996; Fernandez-Cornejo 1998).

The results show that farm experience is a deterrent to the adoption of water-saving technologies. Orchard/vineyard, wheat, alfalfa, hay, and pasture irrigators are more likely to adopt gravity technologies as the farm operator's years of experience on the farm increase. However, only the results for orchard/vineyard, hay, and pasture are significant. 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. One reason for this relationship is that 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).

Crop-specific Water Application Rates

Estimation results for the crop-specific AR models are reported in Table 17. F-stats indicate that all AR equations perform well. The R^2 is relatively low for the pasture equation, suggesting that there may be key variables omitted from that equation.

Results show that physical and economic water scarcities are integral determinants of AR. Discontinued irrigation is associated with lower AR for wheat, alfalfa, hay, and pasture. These results are intuitive. If irrigation water is discontinued long enough to affect yields, some portion of normal irrigation events do not occur. It is reasonable to expect that in this situation the volume of irrigation water applied to each crop (i.e., AR) will decline also. The wheat and pasture equations convey that AR responds positively to surface water price, which can be explained if crop-specific land allocation decisions are considered. It is likely that irrigators also respond to higher surface water prices by allocating a larger proportion of land to less water-intensive crops (Moore, Gollehon, and Carey 1994), such as wheat and pasture (Table 10). In this case, it is possible that even though higher prices likely reduce the total quantity of water demanded (Schoengold, Sunding, and Moreno 2006), mean AR for less water-intensive crops may increase if a large enough quantity of water from that used to irrigate water-intensive crops is reallocated to them.

Every estimated AR equation shows a positive relation between federal water provision and AR, with the effects for orchard/vineyard, wheat, and alfalfa being significant. Irrigators with federal surface water supplies experience mean surface water prices that are 29% lower than for all irrigators (Table 13). These results confirm reports that federal water suppliers, such as the Bureau, subsidize agricultural water supplies (Moore 1999, Moore 1991). All AR equations also show that farms with federal surface water supplies are more price elastic. This effect is only marginally significant in the hay equation. Because irrigators with federally provided surface water tend to experience lower water prices (Table 13) and apply more water to their crops (Table 17), the marginal benefit of AR for these irrigators is likely to be lower. Therefore, because irrigators with federal surface water supplies apply more water to their crops, which results in a lower marginal benefit of AR, their demand curve for AR is flatter and they are more responsive to increasing water prices. 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 reasoning for this process is unclear.

The statistical results demonstrate that climate is a key determinant of AR and that the effects of temperature on AR are more profound than the effects of precipitation. All crop-specific equations show that AR is decreasing in temperature at decreasing rates, with the effects for orchard/vineyard, alfalfa, and hay being significant. AR for orchard/vineyard, alfalfa, and, and hay are minimized at 67°F, 48°F, and 63°F, respectively. However, the minimum temperature experienced by irrigators is 53°F, which is above the estimated threshold for alfalfa of 48°F. This indicates that alfalfa AR always increases in temperature at an increasing rate. 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 for orchard/vineyard and hay is declining in temperature for areas below the threshold level of temperature.

The orchard/vineyard, hay, and pasture equations indicate that AR is increasing in precipitation at a decreasing rate. These relationships imply that orchard/vineyard, hay, and pasture AR are maximized at 0, 39, and 41 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. For example, because precipitation is positive for all irrigators, the orchard/vineyard equation indicates that orchard/vineyard irrigators always respond to increasing precipitation by decreasing AR at an increasing rate. It is unclear why hay and pasture AR is increasing in precipitation for areas below their threshold levels of precipitation.

Results show that producing in a drought region tends to decrease AR for orchard/vineyard and vegetable, with the effects for orchard/vineyard being significant. Wheat, alfalfa, hay, and pasture equations show that producing in a drought region is related to greater AR, with the effects for wheat and hay being significant. Drought areas are typified by greater aridity and soil desiccation (Keyantash and Dracup 2002). Therefore, the results for wheat and hay AR suggest that when irrigators produce under higher levels of aridity and soil desiccation, they tend to increase AR to satisfy crop water needs (Wheeler et al. 2008). The orchard/vineyard and vegetable categories include many more crop varieties than the other crop categories. Therefore, the negative effect of drought on orchard/vineyard AR reflects that with greater aridity and soil desiccation, orchard/vineyard irrigators only cultivate varieties of the lowest water intensity (i.e., AR). For example, vineyards tend to consume notably less water than orchards

(Blaney 1957; USDA 1982), and the USDA (1982) has reported that citrus trees (lemons and oranges) consume about two-thirds the water of other fruit and nut trees (walnuts and peaches).

The orchard/vineyard equation shows that if the farm uses irrigation to mitigate frost damage AR increases. Because frost occurrence typically occurs during the early morning and can be unpredictable, the use of irrigation to mitigate frost damage does not necessarily coincide with scheduled irrigation events. Using irrigation to mitigate frost damage is likely to increase the frequency of irrigation and therefore increase the volume of applied water (i.e., AR). 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).

Geographic qualities of the farm decidedly influence AR. 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. Results reveal that when irrigators only have groundwater supplies they also allocate less water to orchard/vineyard. Farms that are only supplied water from surface or ground sources do not have substitute water supply sources. Therefore, the statistical results suggest that when there are few substitute sources of irrigation water, 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. The reasoning for these results is unclear.

Farm-scale has a positive effect on AR for orchard/vineyard and alfalfa. One reason for this finding is that farms of greater scale have scale economies that lead to lower water prices and greater water use. Table 17 shows that lower-value crops (alfalfa, hay, and pasture) tend to increase AR as land quality increases, with the effects for hay being significant. Table 17 also shows that higher-value crops (orchard/vineyard, vegetable, and wheat) tend to decrease AR as land quality rises, with the effects for vegetable being significant. Table 15 showed that alfalfa, hay, and pasture irrigators have a strong propensity to adopt the water-saving technology when land quality is better. 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. These findings are further supported by the estimated effects of TC on AR.

By conditioning AR on TC it is found 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 also found to result in lower AR, 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 the finding from this research 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 my 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 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" for purchasing water (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.

Table 17. OLS Estimation Results for Crop-specific AR

Variable	Orchard / vineyard	Vegetable	Wheat	Alfalfa	Hay	Pasture
Surface water price	−0.0001	0.0004	0.0046***	−0.0001	−0.0008	0.0031*
	(−0.64)	(0.31)	(4.14)	(−1.07)	(−0.67)	(1.66)
Surface water price × Federal supply	−0.0016**	−0.0042**	−0.0112***	−0.0169***	−0.0104	−0.0097**
	(−2.31)	(−2.23)	(−4.83)	(−3.97)	(−1.36)	(−2.41)
Surface water price × Surface supply	0.0001	−0.0065***	−0.0121***	−0.0044	0.0055	−0.0020
	(1.58)	(−2.74)	(−3.67)	(−1.12)	(0.67)	(−0.48)
Well depth	−0.0001	−0.0001	0.0001	−0.0002	−2.6E−5	−0.0002
	(−0.59)	(−0.43)	(0.72)	(−1.05)	(−0.09)	(−0.63)
Well depth × Ground supply	0.0004	0.0001	0.0001	1.9E−5	0.0003	−0.0001
	(1.54)	(0.12)	(0.37)	(0.03)	(0.41)	(−0.24)
Discontinued irrigation	−0.0805	0.0012	−0.2679***	−0.2378**	−0.2264*	−0.2475*
	(−1.18)	(0.01)	(−3.19)	(−2.24)	(−1.78)	(−1.71)
Population density	0.0005	0.0330	−0.0288	−0.0020	−0.0540	0.0224
	(0.06)	(0.76)	(−0.68)	(−0.03)	(−1.23)	(0.46)
Drought region	−0.2324***	−0.0965	0.4205***	0.1678	0.4544*	0.1818
	(−2.63)	(−0.65)	(3.02)	(1.08)	(1.86)	(0.59)
Frost mitigation	0.1167**	0.0174	—	—	—	—
	(1.97)	(0.14)				
Heat stress mitigation	0.0756	−0.1262	−0.0887	0.0216	—	—
	(1.08)	(−0.90)	(−0.78)	(0.16)		
Temperature	−0.3097***	−0.1867	−0.1553	−0.2788**	−0.6598***	−0.2648
	(−3.34)	(−1.20)	(−1.27)	(−2.16)	(−4.07)	(−0.71)
Temperature squared	0.0023***	0.0015	0.0012	0.0029***	0.0052***	0.0024
	(3.48)	(1.39)	(1.46)	(3.22)	(4.67)	(0.83)
Precipitation	−0.0067	−0.0117	−0.0217	0.0254	0.0315**	0.0412**
	(−0.65)	(−0.80)	(−1.42)	(1.62)	(2.09)	(2.02)
Precipitation squared	−0.0003*	−0.0002	0.0002	−0.0004	−0.0004***	−0.0005**
	(−1.79)	(−1.08)	(1.00)	(−1.50)	(−2.73)	(−2.43)
Federal supply	0.1588**	0.2155	0.4981***	0.5086***	0.1478	0.2625
	(2.15)	(1.55)	(4.19)	(3.46)	(0.75)	(1.60)
Surface supply	−0.2571***	0.0096	0.4191***	−0.1499	−0.1267	−0.0962
	(−3.49)	(0.08)	(3.24)	(−1.01)	(−0.67)	(−0.56)
Ground supply	−0.3636***	0.0314	−0.2817	−0.0583	−0.0468	−0.3182
	(−2.59)	(0.15)	(−1.50)	(−0.25)	(−0.15)	(−1.38)
Land quality	−0.0845	−0.8229**	−0.4351	0.4326	1.3310***	0.4750
	(−0.39)	(−2.18)	(−1.45)	(1.45)	(3.18)	(0.86)
Farm-scale	0.0004***	0.0004	−0.0001	0.0009**	0.0002	−0.0001
	(3.00)	(1.51)	(−0.03)	(2.22)	(0.49)	(−0.04)
Waste disposal	—	—	—	—	—	−0.3328
						(−0.99)
Sprinkler TC[a]	−0.1795*	−0.5399***	−0.3172***	0.0592	0.0941	0.1106
	(−1.85)	(−3.64)	(−3.02)	(0.46)	(0.77)	(0.71)
Drip TC	−0.1261*	−0.3945**	—	—	—	—
	(−1.80)	(−2.54)				
Tenure	0.0573	0.1394	0.1079	−0.0448	0.0531	−0.1134
	(1.06)	(1.27)	(1.26)	(−0.50)	(0.45)	(−0.89)
Internet	0.0518	0.3191**	0.0090	0.2006*	0.1240	0.1938
	(0.54)	(2.07)	(0.08)	(1.92)	(0.90)	(1.25)
Farm occupation	0.1285*	0.0194	0.2703	0.1290	0.2587	0.1372
	(1.71)	(0.13)	(1.59)	(0.79)	(1.34)	(0.85)
Farm experience	−0.0001	0.0039	0.0021	0.0035	0.0026	0.0029
	(−0.03)	(1.13)	(0.73)	(1.19)	(0.65)	(0.73)
Intercept	11.6557***	8.7440	6.5750	7.7387	21.3184***	8.2207
	(3.49)	(1.60)	(1.50)	(1.64)	(3.57)	(0.67)
Observations	483	384	501	651	416	356
R^2	0.26	0.44	0.36	0.52	0.37	0.15
F-stat. (df)	5.09 (457)	8.91 (358)	10.31 (477)	19.11 (627)	7.79 (393)	3.43 (332)

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

Endnotes

[1]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. 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).

[2]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).

[3]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).

[4]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).

[5]According to Carey and Zilberman (2002), with uncertainty in 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.

Policy Implications

The most important policy implications found involve asset heterogeneity and the distributional effects of agricultural policy. Several findings from this research provide valuable information about how irrigators would respond and adapt to climate change. The current findings also lead to commonly advocated revisions to federal water subsidy policies. Some key differences between the irrigation choices of higher- and lower-value crops were also identified. Identifying these differences sheds further light on the distributional consequences of agricultural policy. Many findings from this research 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, the data used in this research has a large degree of variation in water scarcity and climatic factors, making the 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; Schaible, Kim, and Whittlesey 1991). The statistical results showed that specific crops have a proclivity for certain irrigation technologies that can mitigate particular climatic stressors. The 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 these crops 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. Therefore, with climate heterogeneity, the distribution of water policy impacts depends on prior land allocation decisions such as crop choices. This finding has high policy relevance for agricultural landscapes where cropping patterns and climate conditions are particularly diverse, such as on the West Coast.

Results suggest that water pricing policies encourage adoption of the water-saving technology (sprinklers) for wheat and alfalfa when these crops are exposed to heat stress because sprinklers can also mitigate heat stress to them. However, water pricing policies do not encourage adoption of the most water-saving technology (drip) for orchards and vineyards that are exposed to heat stress 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.

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). By contrast findings from the current research demonstrate that incompatibility between certain irrigation technologies and cropping patterns can arise from heterogeneity in climate conditions. It was found that surface water price, well depth, groundwater supply, and production in a drought region promoted the adoption of water-saving sprinklers, but not the most water-saving technology (drip) for vegetable. Similar results were demonstrated for orchard/vineyard. These results corroborate 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).

Results conveyed 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 (Figure 5), where irrigators have been diverting water from the Russian River to acquire water for frost protection.[1] 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.

Several results from this research 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). The results indicated that for several crops the discontinuance of irrigation water (i.e., water supply or price 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).

The effects of temperature and precipitation on irrigation choices were thoroughly investigated. The effects of temperature on irrigation choices were more profound than the effects of precipitation. For TC and AR, temperature and precipitation were often 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, it was 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.

Results depicted that irrigators respond to higher water prices by increasing the intensive margin of water demand for the least water-intensive crops. This result likely follows the reallocation of land to crops of lower water-intensity as prices rise. Evidence was found that when a farm produces in a drought region, irrigators respond by cultivating crop varieties of the lowest water intensity (i.e., AR). These findings indicate that under conditions of economic water scarcity or drought, farms will allocate water to crops with the greatest value per unit of applied water (Jackson et al. 2011). It was also shown 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. Evidence was found that federal water subsidies (Moore 1999; Moore 1991) make irrigators more responsive to water price at the farm-level extensive proportion and crop-level intensive margin, and create disincentives to invest in water-saving technologies. The Bureau is, by far, the nation's largest (federal) 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.

Key differences were identified between the irrigation choices made for higher-value and lower-value crops. The results suggest that on the West Coast, economies of smallness (Dinar, Yaron, and Voet 1992) only exist for lower-value crops. Strong evidence was also found that irrigators tend to choose more advanced irrigation technologies and higher water application rates for lower-value crops on higher quality land. Supporting evidence for this finding was provided by the result that adoption of water-saving technologies only reduces water application rates 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 effectiveness and distributional impacts of agricultural policies will be dependent on the distributions of land quality and cropping patterns in the relevant policy region (i.e., land quality heterogeneity).

Endnotes

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

Conclusion

This paper addressed irrigation choices with a particular focus on the effects of water scarcity and climate. This was accomplished through estimated models of cropland 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 indicate 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 exhibit important influences on irrigation choices. Findings from this research provide valuable information about the distributional effects of agricultural policy and how irrigators would respond and adapt to future climate change.

Results showed that the discontinuance of irrigation water reduces water demand at the farm-level extensive proportion (i.e., PI) and crop-level intensive margin (i.e., AR), and creates an option value that delays and discourages adoption of water-saving technologies. The effects of temperature and precipitation on irrigation choices were often found to be crop-dependent and quadratic-like. The effects of temperature on irrigation choices were found to be more profound than the effects of precipitation. I 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). Federal water provision was found to have salient effects on all three components of irrigation choice and evidence the effects of subsidized water supplies on these choices. Other implications related to the distributional effects of agricultural 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 (Rötter and van de Geijn 1999). Crop-specific modeling offers a means for identifying climate 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 study region with large variation in climate conditions, this research 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 the estimated 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). That example highlights the importance of incorporating knowledge of interdisciplinary science (e.g., plant biology) when investigating crop-specific irrigation choices. It was also found that on the West Coast, economies of smallness (Dinar, Yaron, and Voet 1992) only exist for lower-value crops, which should be validated. Future crop-specific irrigation choice studies would benefit from panel micro data 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.

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Appendix

Complete Coefficient Estimation Results

Table A.1. Tobit Estimation Results of PI

Variable	Coef.	Asymp. t-stat.
Surface water price	−3.9E−5	−0.65
Surface water price × Federal supply	−0.0011**	−2.36
Surface water price × Surface supply	−0.0002	−1.31
Well depth	3.9E−5	0.68
Well depth × Ground supply	4.2E−5	0.37
Discontinued irrigation	−0.0657**	−2.11
Population density	−0.0197***	−3.34
Drought region	0.0781*	1.81
Temperature	−0.0726**	−2.19
Temperature squared	0.0006***	2.73
Precipitation	0.0085**	2.39
Precipitation squared	−0.0001**	−2.49
Federal supply	0.2528***	7.26
Surface supply	0.0697**	1.96
Ground supply	0.0637	1.21
Land quality	0.4771***	5.84
Farm-scale	−0.0022***	−5.98
Orchard/vineyard[a]	0.1786***	5.59
Vegetable	0.1732***	5.66
Wheat	0.0705**	2.45
Hay	−0.0838***	−2.98
Pasture	−0.0710**	−2.44
Waste disposal	0.2591***	3.71
Tenure	0.0182	0.69
Internet	−0.0342	−1.03
Farm occupation	−0.0064	−0.19
Farm experience	−0.0039***	−4.80
Intercept	2.6115**	2.18
Observations		1,461
Uncensored observations		791
Right-censored observations at PI=1		670
McFadden R^2		0.23
Squared correlation		0.29
LR chi^2 (df=27)		472.39

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. Estimation Results from Multinomial Logits of TC

	Orchard/vineyard		Vegetable	
Variable	Sprinkler	Drip	Sprinkler	Drip
Surface water price	−0.0036	0.0002	0.0152*	0.0131
	(−1.44)	(0.49)	(1.82)	(1.52)
Surface water price × Federal supply	0.0038	0.0084	−0.0070	−0.0076
	(0.39)	(0.93)	(−0.79)	(−0.80)
Surface water price × Surface supply	0.0190**	0.0143*	−0.0003	0.0071
	(2.44)	(1.93)	(−0.04)	(0.80)
Well depth	0.0008	0.0013	0.0020**	0.0011
	(0.77)	(1.43)	(2.10)	(1.09)
Well depth × Ground supply	−0.0020	−0.0020	−0.0027	−0.0011
	(−1.09)	(−1.28)	(−1.01)	(−0.39)
Discontinued irrigation	−0.9773*	−0.7152*	−0.7164	−0.1336
	(−1.87)	(−1.75)	(−1.48)	(−0.23)
Population density	0.0054	0.0135	−0.5312**	−0.1974
	(0.08)	(0.25)	(−2.55)	(−0.84)
Drought region	0.9324	0.3082	0.9763	−0.3574
	(1.57)	(0.61)	(1.51)	(−0.48)
Frost mitigation	1.2457***	0.8150**	1.6846***	0.5967
	(2.98)	(2.18)	(3.09)	(0.84)
Heat stress mitigation	0.2069	−0.6285	−0.5938	−0.5320
	(0.38)	(−1.21)	(−1.10)	(−0.71)
Temperature	−2.2964*	−2.0390	0.5056	0.9063
	(−1.71)	(−1.56)	(0.93)	(1.05)
Temperature squared	0.0153	0.0140	−0.0044	−0.0062
	(1.59)	(1.50)	(−1.22)	(−1.05)
Precipitation	−0.1237	−0.1660**	−0.2122***	0.0322
	(−1.43)	(−2.06)	(−3.00)	(0.25)
Precipitation squared	0.0025*	0.0028*	0.0038***	−0.0016
	(1.66)	(1.92)	(3.42)	(−0.55)
Federal supply	0.2689	0.1351	−0.7243	−0.8314
	(0.42)	(0.23)	(−1.43)	(−1.19)
Surface supply	−0.6975	−0.9886*	−0.0309	−0.2840
	(−1.09)	(−1.71)	(−0.06)	(−0.36)
Ground supply	0.3517	0.4658	2.4288*	1.1674
	(0.46)	(0.70)	(1.76)	(0.78)
Land quality	1.4703	0.5668	−0.9905	−0.4830
	(1.02)	(0.47)	(−0.72)	(−0.26)
Farm-scale	0.1729*	0.2382***	0.0478	0.0960**
	(1.85)	(2.78)	(1.02)	(1.99)
Crop diversity	−0.2497	−0.3423*	−0.1850	−0.6267***
	(−1.26)	(−1.94)	(−1.10)	(−2.72)
Tenure	0.1441	−0.2015	0.0078	0.9583**
	(0.35)	(−0.55)	(0.02)	(1.84)
Internet	−0.0766	0.9894**	0.8306	0.6549
	(−0.16)	(2.34)	(1.48)	(0.96)
Farm occupation	−0.0500	−0.6756	−0.8424	0.4406
	(−0.10)	(−1.52)	(−1.20)	(0.47)
Farm experience	−0.0288**	−0.0330***	−0.0148	0.0001
	(−2.35)	(−3.13)	(−1.18)	(0.01)
Intercept	86.7555*	77.1844*	−10.2467	−32.8188
	(1.87)	(1.70)	(−0.51)	(−1.04)
Observations	485		386	
McFadden R^2	0.26		0.36	
LR chi^2 (df=48)	250.91		261.90	
Correct prediction	67%		76%	

Note: Terms in parathesis 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 A.3. Estimation Results from Binomial Logits of TC

Variable	Wheat Sprinkler	Alfalfa Sprinkler	Hay Sprinkler	Pasture Sprinkler
Surface water price	0.0027	0.0002	−0.0002	0.0034
	(0.68)	(0.18)	(−0.05)	(0.70)
Surface water price	0.0149**	0.0060	0.0022	−0.0058
× Federal supply	(2.02)	(0.54)	(0.25)	(−0.88)
Surface water price	−0.0236**	−0.0028	0.0006	0.0033
× Surface supply	(−2.38)	(−0.31)	(0.07)	(0.51)
Well depth	0.0018**	0.0004	0.0017	0.0003
	(1.98)	(0.50)	(1.60)	(0.32)
Well depth	−0.0024	−0.0010	0.0013	0.0004
× Ground supply	(−1.18)	(−0.53)	(0.69)	(0.18)
Discontinued irrigation	−0.6482*	−0.5196*	−0.3876	−0.5030
	(−1.67)	(−1.75)	(−1.20)	(−1.32)
Population density	0.0345	0.0828	0.0571	−0.0192
	(0.17)	(0.70)	(0.48)	(−0.11)
Drought region	0.5447	0.3762	0.6452	1.3234*
	(0.96)	(0.79)	(1.12)	(1.74)
Heat stress mitigation	0.9005	2.8404***	—	—
	(1.60)	(3.50)		
Temperature	1.9659***	1.7814**	4.3885***	6.7333***
	(3.03)	(2.30)	(6.25)	(7.28)
Temperature squared	−0.0172***	−0.0162***	−0.0347***	−0.0524***
	(−3.60)	(−2.78)	(−6.39)	(−7.24)
Precipitation	−0.1592***	0.0174	0.0832*	0.0977*
	(−2.92)	(0.32)	(1.79)	(1.81)
Precipitation squared	0.0018**	0.0001	−0.0004	−0.0005
	(2.41)	(0.14)	(−0.81)	(−0.81)
Federal supply	−1.2786***	0.2020	0.2813	0.3179
	(−2.94)	(0.46)	(0.74)	(0.79)
Surface supply	−0.1468	−0.3050	−0.1576	−0.3261
	(−0.28)	(−0.71)	(−0.35)	(−0.71)
Ground supply	2.2554*	1.6640**	0.9651	0.6613
	(1.95)	(2.10)	(1.30)	(0.85)
Land quality	0.0439	3.7952***	4.1254***	9.5456***
	(0.04)	(3.56)	(3.79)	(6.79)
Farm-scale	−0.0041	−0.0008	−0.0016	−0.0315*
	(−0.21)	(−0.17)	(−0.78)	(−1.70)
Crop diversity	0.1366	0.0028	0.6149***	−0.0268
	(0.93)	(0.02)	(3.94)	(−0.17)
Waste disposal	—	—	—	3.4457***
				(2.94)
Tenure	0.2495	−0.3549	0.1434	−0.0294
	(0.68)	(−1.23)	(0.52)	(−0.09)
Internet	0.5963	0.7034**	−0.1459	−0.2244
	(1.49)	(2.06)	(−0.41)	(−0.56)
Farm occupation	−0.3351	0.1617	−0.4384	0.0155
	(−0.57)	(0.37)	(−1.14)	(0.04)
Farm experience	−0.0068	−0.0134	−0.0194**	−0.0179*
	(−0.64)	(−1.51)	(−2.11)	(−1.66)
Intercept	−52.4848**	−48.2958*	−141.7548***	−219.5232***
	(−2.32)	(−1.85)	(−6.04)	(−7.23)
Observations	501	651	416	356
McFadden R^2	0.48	0.53	0.33	0.38
LR chi^2 (df)	321.34 (23)	456.94 (23)	188.13 (22)	186.40 (23)
Correct prediction	87%	88%	79%	80%

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.