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Economic Impacts of Climate Change on Agricultural Water Use in California

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Preliminary Economic Analyses of Climate Change Impacts and Adaption and GHG Mitigation contract, contract number 500-02-004, Work Authorization MR-006, by the University of California, Berkeley.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

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Abstract

Economic Impacts of Climate Change on Agricultural Water Use in California describes part of a broad spectrum of studies of the California water system that are being conducted to assess the impacts of climate change on urban and agricultural water agencies. Study topics include methods for measuring the economic value of water supply reliability to water users in California, and methods for projecting changes in supply reliability caused by climate change. This report describes preliminary work on the first topic. To measure water supply reliability, researchers collected data on several variables, including water deliveries for project districts spanning 20 years, water rights information, water source information and electricity use data related to groundwater pumping. To measure the economic value of reliability, they collected land value, water price, water transfers for many years, and cropping by districts. The project found that the average magnitude of change in farmland value due to a potential decrease in water availability appears to be larger than that caused by an increase in temperature. This finding suggests that the impact on the availability and reliability of water supply may be the crucial pathway by which climate change affects California agriculture.

Executive Summary

Climate change in California is a source of growing concern; the various impacts it will have on the state's agricultural industry could be potentially damaging. Major economic impacts are likely to be manifested through the state's water system.

This project's objective is to assess the economic costs associated with potential changes in the reliability of supply for water users in various parts of the state. Previous research on water use in California has generally used data gathered from broad geographic aggregates. This research differs in that it gathered and analyzed data from individual water districts; which is necessary, because there is considerable heterogeneity among different water districts in California with regard to water source, the nature and age of water rights, the operational costs, finances, price structures, and other terms of service.

To assess the impacts that climate change in California is likely to produce, with regard to the existing mismatch between both where and when rains falls and where and when people need to use water, researchers at the University of California, Berkeley, are conducting a broad spectrum of studies on the California water system, including six main components: (1) determining the existing reliability (degree of certainty) of the water supply for various irrigation districts and urban water agencies around the state; (2) conducting an econometric analysis, which will measure the economic consequences of differences in supply reliability and ultimately will be used to develop economic loss functions for changes in agricultural water supply reliability caused by climate change; (3) conducting an econometric analysis based on cross-section and time-series data on urban water use for urban water agencies in California to estimate demand functions for water, which will determine the demand elasticities that will be used to project future urban water demand in areas of new urban growth in California; (4) projecting future agricultural and urban water demand and supply in California in the absence of climate change; (5) assessing how climate variability and change will impact the reliability of water supply for urban and agricultural water agencies in California by evaluating alternative models to estimate the impact of climate change on water supply; and (6) assessing the economic consequences of the future changes in supply reliability for California's urban and agricultural water users as a result of climate change. The research reported here focuses on the first and second of these components.

To measure water supply reliability, researchers collected data on several variables, including water deliveries for project districts spanning 20 years, water rights information, water source information and electricity use data related to groundwater pumping. To measure the economic value of reliability, they collected land value, water price, water transfers for many years, and cropping by districts. These data are illustrated in Section 2 of the report.

Section 3 focuses on an econometric analysis of how climactic variables and access to surface water are capitalized into farmland values among different irrigation districts in California, and how farmland values would be affected by climate change. The results are highly consistent with the agronomic literature on the effect of growing degree-days on plant growth.

The average magnitude of change in farmland value due to a potential decrease in water availability appears to be larger than that caused by an increase in temperature. This finding suggests that the impact on the availability and reliability of water supply may be the crucial pathway by which climate change affects California agriculture.

Obviously, this analysis does not incorporate the effect of every variable associated with climate change. The study focused primarily upon two variables—temperature and water supply—and excluded others that were believe to be less influential. Variables excluded from this analysis that may nevertheless have important moderating impacts include reduced evapotranspiration and carbon fertilizing associated with rising carbon dioxide levels. In addition, changing technology and policy variables, such as mandated efficiency standards, may impact the future demand for water. However, this analysis may indirectly incorporate the effect of these variables, to the degree that farmers and landowners anticipate their influence on the market for agricultural land.

1.0 Introduction

The major pathway by which climate change will affect the California economy is through its impact on the California water system. Therefore, a major component of the climate change research being conducted at the University of California, Berkeley, is an economic analysis of the California water system to assess the economic costs associated with changes in the reliability of supply for water users in various parts of the state.

Compared to previous research, the approach that the research team has adopted for measuring the economic impacts of climate change has two distinctive features.

First, the primary spatial unit of analysis is the service areas of individual retail water supply agencies—irrigation districts and urban water agencies—as opposed to broader geographic aggregates of districts such as depletion analysis areas. To the maximum extent possible, this analysis will be disaggregated to the level of the individual water district. It is important to avoid any further aggregation, because there is tremendous heterogeneity among different water districts even within the same county in California with respect to their water source, the nature and age of their water rights, their operational costs, their finances, the price they charge their retail customers, and other aspects of their terms of service. Because of this diversity, aggregation is likely to be misleading and to introduce error into the analysis.

Second, unlike previous studies, this study focuses explicitly on supply *reliability* and the *uncertainty* over supply that confronts water users around the state at the time they make their important water use decisions. Researchers seek to measure this explicitly, both in the baseline situation and in climate change scenarios, because they believe that climate change in California is likely to affect water users primarily through its impact on supply reliability and uncertainty. This has not been analyzed in the existing work on climate change in California.

In this context, it is important to note the uneven temporal distribution of water supply and water use in California: roughly 80% of the state's precipitation falls between October and March, but about three quarters of all the water use in California occurs in the spring and summer, between April and September. What happens—or does not happen—during that period is the key to whether the state's economy is benefited or harmed by water supply that year. Moreover, many important decisions that determine water use during this period are made *at the beginning* of the period. Farmers decide which crops to plant (and whether or not to replace perennials) in the early spring, around March or early April. Once they have made that decision, they are limited in the degree to which they can vary their use of water during the growing season—they can under-water their crops, or even abandon them, if it subsequently happens that they receive less water than they had anticipated at the time of planting, but they cannot switch to a different crop nor is it practical for them to make a major change in irrigation technology during the growing season. With urban water use the context is somewhat different, but there is still a critical window for decision around April in that, if urban water managers think there is a fair chance that they will experience some degree of water shortage during the coming warm season, they generally need to put out a call for voluntary (or mandatory) conservation no later than the end of spring. This sets up a pattern of water demand in their service area over the summer that is likely to be, at best, only partially reversible if water supplies turn out to be more abundant than originally anticipated.

For somewhat similar reasons, environmental water managers in California, too, face a key decision point around April: because of the time lags in securing water supplies and arranging for their transfer, if managers are to meet critical in-stream needs during the warm season they will need to take action by the end of spring. For these reasons, much of the water use that occurs in California between April and September is likely to be determined by water agencies' *expectation*s, as of the beginning of this period, regarding the amount of water that will become available to them during the coming summer. Supply reliability needs to be assessed by reference to these expectations.

Most of the existing hydrologic/economic models—both in California and elsewhere—deal with supply uncertainty by ignoring it. They represent water supply using the actual, historical monthly deliveries. This approach amounts to characterizing uncertainty by the *ex post* realization of the random variable, which effectively eliminates the uncertainty. However, as explained above, given the timing of water use decisions in California it is clearly the *ex ante* probability of obtaining water during the warm season (late spring and summer), as assessed some time around March or April, that has the most powerful influence on water users' decisions in California. Furthermore, it is reasonable to expect that these decisions will typically exhibit a significant degree of *risk aversion*. The important implication is that water use decisions are likely to depend not just on the mean of the ex ante probability distribution of warm-season water supply, but also on other parameters of the distribution, such as the semi-variance or the tail probabilities. In order to develop a linkage between changes in supply reliability and consequent economic impacts, one has to characterize supply reliability in terms of relevant parameters of the ex ante probability distribution of warm-season water supply. Given the observations above about the heterogeneity among water districts with regard to their water supply, these distributions generally need to be assessed for each district separately.

Implementing this approach, with its novel focus on measuring supply reliability at the level of individual water districts, is a major challenge, because of the limitations in the data that are readily available in California. It is easy to obtain data on historical water deliveries for the two big projects (the Central Valley Project (CVP) and State Water Project(SWP)) and for groups of irrigation districts combined into depletion study areas (DSAs). Obtaining historical delivery data for individual districts not served by the two projects is often difficult. Obtaining a representation of the likely expectations of district managers in the form of an ex ante probability distribution is a major research task that has not previously been undertaken in California.

To deal with problems caused by the limited availability of data, this study is pursuing a flexible and iterative strategy that iterates between data collection and data analysis. In the first year of research, researchers started by collecting the most readily available data and then pushed on to conduct a preliminary analysis of these data—recognizing that, although the data are still incomplete, many methodological issues arise during the course of data analysis, and it is useful to start confronting them as early in the research as possible. While conducting the preliminary data analysis, this study continues to expand the data and fill in the gaps. After a second round of data collection efforts, researchers will take a second crack at the data analysis, while still continuing with efforts to complete the data collection and with a view to a subsequent final data analysis. Thus, rather than working in sequence, researchers are conducting the various components of this analysis in parallel.

In California, climate change is likely to severely exacerbate the existing mismatch between where and when rain falls and where and when people need to use water. To assess these impacts, researchers are conducting a broad suite of studies on various aspects on the California water system. The overall research involves six main components:

> (1) Measure the existing reliability (degree of certainty) of the water supply for various irrigation districts and urban water agencies around the state, given their various sources of supply, and their water rights or water contract entitlements. To accomplish this task researchers identify specific water users (agricultural and urban) who will be the focus of the study, and assemble a database of information on their water supply (e.g., contractual water entitlements, water rights, other sources of supply, within-district storage); their water demand (e.g., cropping pattern, population, number of industrial, commercial and residential customers); and the economic value of water to their customers (e.g., water costs and pricing, crop prices, other input prices, farmland values).
>
> (2) Conduct an econometric analysis based on cross-section and time-series data of the relationships between supply reliability and economic outcomes for irrigation districts in California, including agricultural practices, choice of crops, farm profit, and land values. These relationships measure the economic consequences of differences in supply reliability, and will be used to develop economic loss functions for changes in agricultural water supply reliability.
>
> (3) Conduct an econometric analysis based on cross-section and time series data on urban water use for urban water agencies in California to estimate demand functions for water. The resulting short- and long-run price elasticities of demand will be used to develop short- and long-run loss functions for shortages in urban water supply in California. The demand elasticities with respect to conservation variables will be used to assess the future potential for reducing urban demand via conservation. The demand elasticities with respect to climate variables, housing density, and housing vintage will be used to project future urban water demand in areas of new urban growth in California.
>
> (4) Project future agricultural and urban water demand and supply in California in the absence of climate change, based on economic and demographic scenarios, and projections of land use conversion and patterns of future urban growth in California. This analysis will incorporate results from the econometric analyses conducted in (2) and (3).

(5) Assess how climate variability and change will impact the reliability of water supply —the ex ante probability distributions—for urban and agricultural water agencies in California. This task evaluates alternative models to estimate the impact of climate change on water supply and the factors that determine runoff forecasting and how they relate to climate inputs (e.g., how the amount of water stored in the snowpack affects the accuracy in forecasting).

(6) Assess the economic consequences of the future changes in supply reliability for urban and agricultural water users in California identified in (5) when applied to the future scenarios developed in (4), using the economic loss functions developed in (2) and (3).

This report describes the work that has been done on items (1) and (2).

2.0 Agricultural Water Supply, Cropping Patterns, and Land Values

Water supply uncertainty is assessed at the district level, because the source and cost of water, the reliability of water supply, and the available quantity of water supply all vary primarily across districts. Water supply and price variation exists within districts as well, but it is comparatively limited. To implement a district-based research approach, researchers have been creating a database with information on these variables, which permits them to better assess the uncertainty of existing water supplies and to project changes in future supply uncertainty as the result of climate change.

To measure water supply reliability at the district level, researchers collected data on several variables, including deliveries for project districts spanning 20 years, supply forecasts for project districts spanning 20 years, some water rights information, water source information, and electricity use data related to groundwater pumping. To measure the economic value of reliability they collected land value, water price, water transfers for many years, and cropping by districts. The climate data collected includes PRISM data, showing 100-year run minimum and maximum monthly temperatures and precipitation for four grid points surrounding each farm observation. The population dataset for this study covers each of 7049 Census tracts in California; the soil data is derived from the STATSGO soil survey. Researchers have a very detailed database of groundwater, constructed from more than 16,000 well observations. The surface water rights data includes information about project entitlements to Districts from the Central Valley and State Water Projects. Water rights information also came from the ACWA (Association of California Water Agencies) database. Water price data was obtained from ACWA and the Irrigation Water Rates Manual.

This section illustrates some of the data that has been collected, with a series of maps and charts, including data about water source, surface water supply, water transfer, cropping and land values in agricultural districts in the Central Valley. These results clearly indicate that there are large differences among districts in the Central Valley with respect to water supply reliability, water sources, water rights, land values, and cropping patterns—all of which greatly affect agricultural water use in California.

2.1. Water Source Variability

The water source map for the San Joaquin County illustrates how water source varies by district (Figure IIIA-1). In this map, districts in the west side obtain largely surface water (regions shown in blue). Districts in the northeast pump groundwater for the most part (region shown in yellow). Finally, districts in the southeast obtain water from both ground and surface sources (region shown in green).

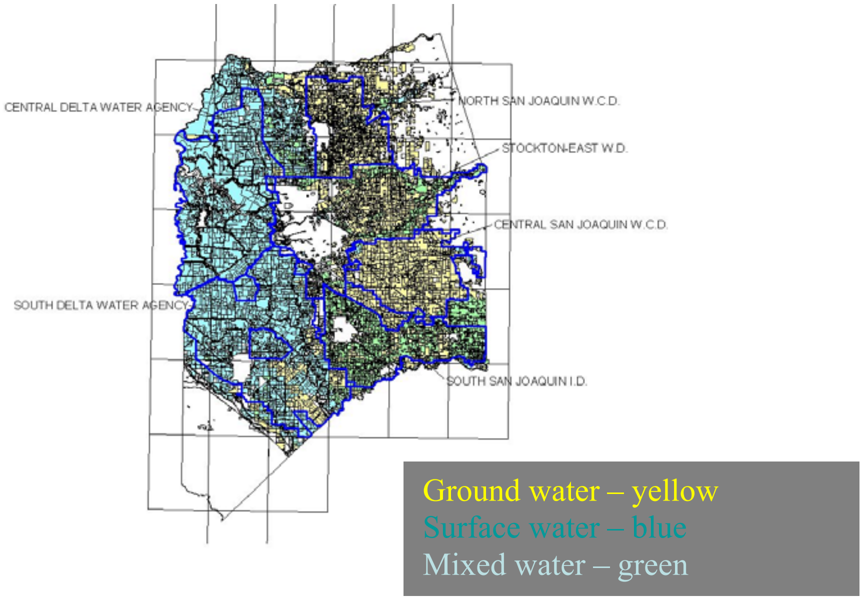

Figure 2-1. Water Source Variability in San Joaquin County

2.1.1. Surface Water Supply Variability

Water supply variability is illustrated through the results of CALSIM II model runs and also with data on water deliveries to water districts in the Sacramento and San Joaquin Valleys.

2.1.1.1. Model Runs

The most recent available simulations runs for CALSIM-II—known as the Benchmark Studies (DWR/USBR 2002)—contain monthly data for the demands and deliveries for different water users in the Californian water system. Using the available monthly data on demands and deliveries (only surface water deliveries), researchers calculated monthly and annual quantity-based reliability measures defined as the percentage of water delivered compared to a target delivery level represented by the water demand.[1] With both the monthly and annually reliability measures researchers constructed frequency curves of these values and calculated an overall reliability measure (Figure 2-2).

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[1] This definition is based on Hashimoto et al. (1982) and Bogardi and Verhoef (1995). A time-base definition of reliability would be the fraction of time a system is under a no-failure mode defined by a certain target. Other measures of a system performance not included in this analysis are the vulnerability and resilience (see Hashimoto et al. (1982).

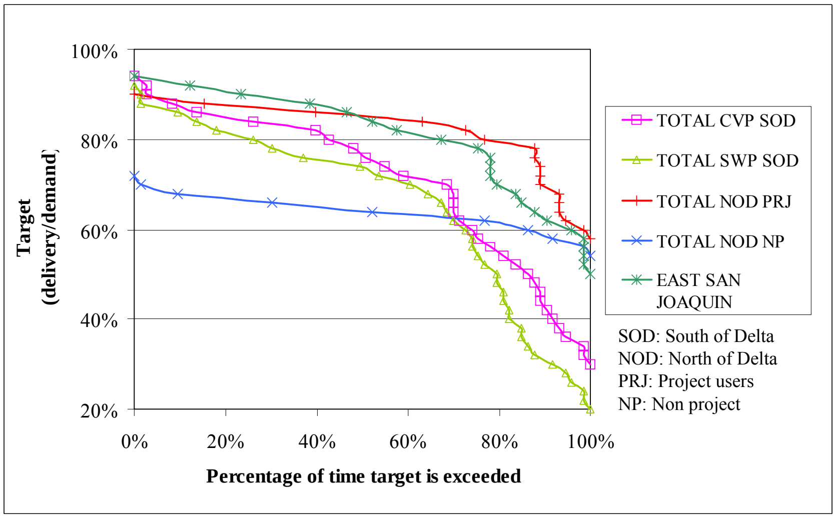

Figure 2-2. Variability of Surface Supply by User Group

The analysis was done for different types of users according to their geographic location, their source of water and different water rights status. These different users were also aggregated into different levels. The first level considered the whole Central Valley system.[2] The second level compared reliability measures for broad geographic categories of users: North of the Delta (NOD) Project and non-project users; State Water Project (SWP) South of the Delta (SOD) users; Central Valley Project (CVP) SOD users; and East San Joaquin users. Figure 2-2 shows a map of these broad categories of users. The third and final level went within some of these groups to assess the reliability for more specific type of users.[3] An example of the analysis done at this step was the comparison of the reliability among different types of CVP users SOD (i.e. Between Exchange, Agriculture, Municipal and Industrial (M&I), and Refugee Contractors). The reliability curves are presented in a series of figures. These curves should be read first looking at a delivery target (say 50% of demand) along the x axis, and then at the percent of time this target is equaled or exceeded on the x axis.

2.1.2 Surface Deliveries

Researchers collected information showing surface water deliveries to water districts across the Central Valley. The information gathered includes data showing surface deliveries from project sources (state and federal projects), local water deliveries to non-project districts, riparian withdrawals, and local canal company deliveries. The information was provided from a variety

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[2] Only Delta users were not considered in the analysis, because there are some concerns about the corresponding CALSIM-II results that need to be discussed with the DWR.

[3] Using CALSIM-II it is also possible to analyze of the reliability at the ID district level, but there is no good representation of these users, yet so we preferred not to do it at this time.

of sources, including the regional offices of the California Department of Water Resources (DWR), individual water district offices, consultants, and officials from the State Water Resources Control Board (SWRCB). The data from these sources were combined with cropping data to show total surface deliveries per cropped acre. The information is stored in a series of access databases, Excel spreadsheets, and geographical information systems (GIS) databases.

The information about surface water deliveries contained in the GIS database is illustrated for a subset of districts in the San Joaquin Valley (Figure 2-3). It is apparent that districts within the same county have widely different water supplies. In particular, districts in the eastern and northern portions of the San Joaquin Valley have relatively large surface water supplies, compared to other districts in the Valley.

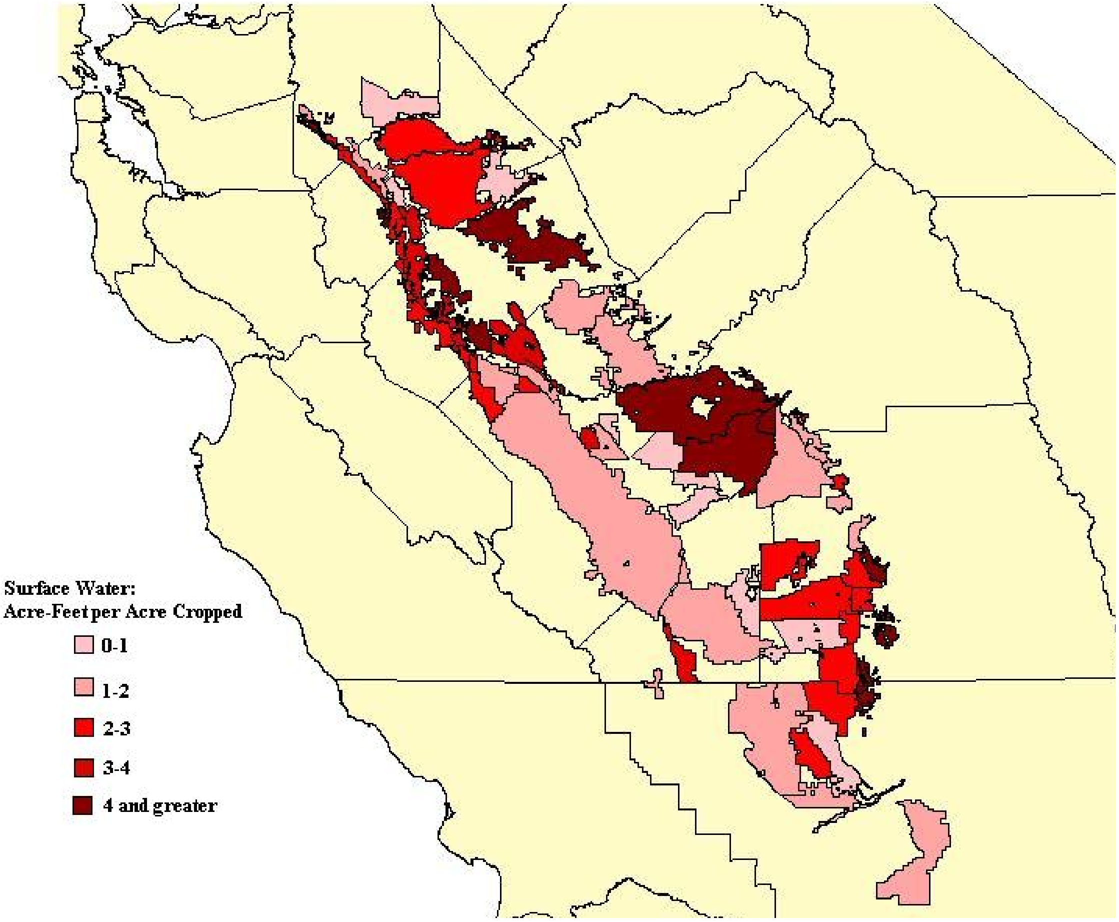

Figure 2-3. Surface Water Deliveries by District in the San Joaquin Valley

2.1.3 Groundwater Depth and Access

Researchers collected two sets of well depth measurements: time series for the Sacramento Valley and time series for the San Joaquin Valley. Each set has hundreds of thousands of well measurements over several years (1950–2000). This data is detailed with almost all of the well measurements taken within cropping areas of the Central Valley, usually before and after the growing season. The well measurements show depth to groundwater.

Over certain areas there appears to be a bi-model distribution of groundwater depths, reflecting well depths in shallow and deep aquifers (Figure 2-4). Over other areas, researchers plan to develop functions summarizing groundwater depths over time and location within the Central Valley.

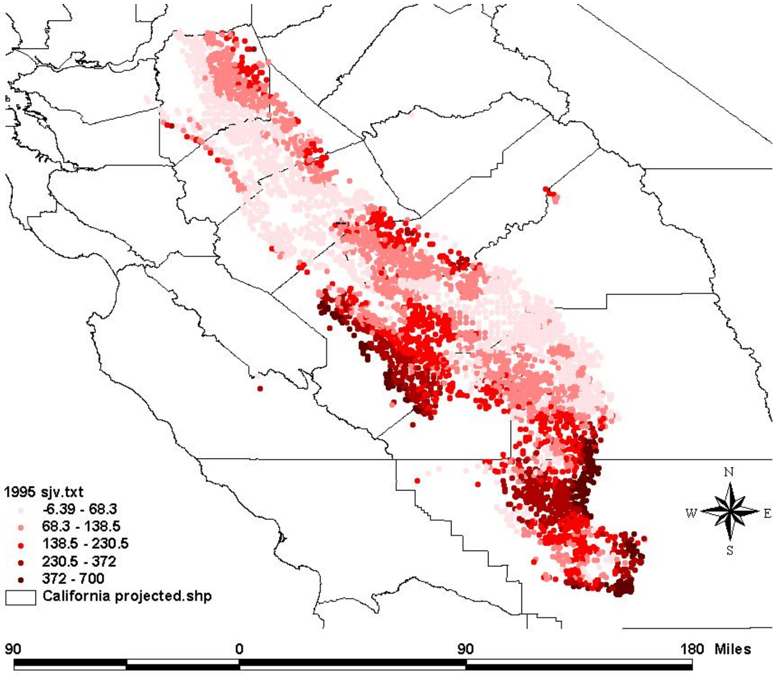

Figure 2-4. Groundwater Depth in the Central Valley

2.1.4 Availability of Water Transfers

Flexible water markets can help efficiently distribute water across the state during periods of drought. Climate change in California will likely decrease agricultural water supplies and increase water demands. Therefore, the impacts of climate change will vary depending on the extent that participants adopt flexible market structures to reallocate water supplies and regulate groundwater storage.

Water markets have potential to limit economic losses within agricultural areas under periods of stress. For example, a recent drought study focused on the Delta Mendota region, suggests that water shortage may lower gross state product $175 million without water markets (shortages concentrated in the Delta-Mendota region) and by only $20 million with water markets (shortages shared across all growers; with rules allowing water trading) (Zilberman 2002).

Water markets between agricultural and urban areas are particularly valuable, helping as they do to prevent urban drought shortages.

Currently, the overall volume of trading in the different water markets is relatively small. In the researchers' database, the most water traded in a single year was about 800,000 acre-feet.[4] Most of this trading was between agricultural districts. Currently only a handful (11 out of some 200) of water districts have sold water to urban areas, despite continued efforts by urban areas to buy water (Figure 2-5). Of course, agriculture to urban transfers are limited by the level of urban demand for water in the state. However, rapid urban growth suggests the demand for low cost agricultural water supplies exceeds the supply in many parts of the state for reasons that have yet to be worked out.

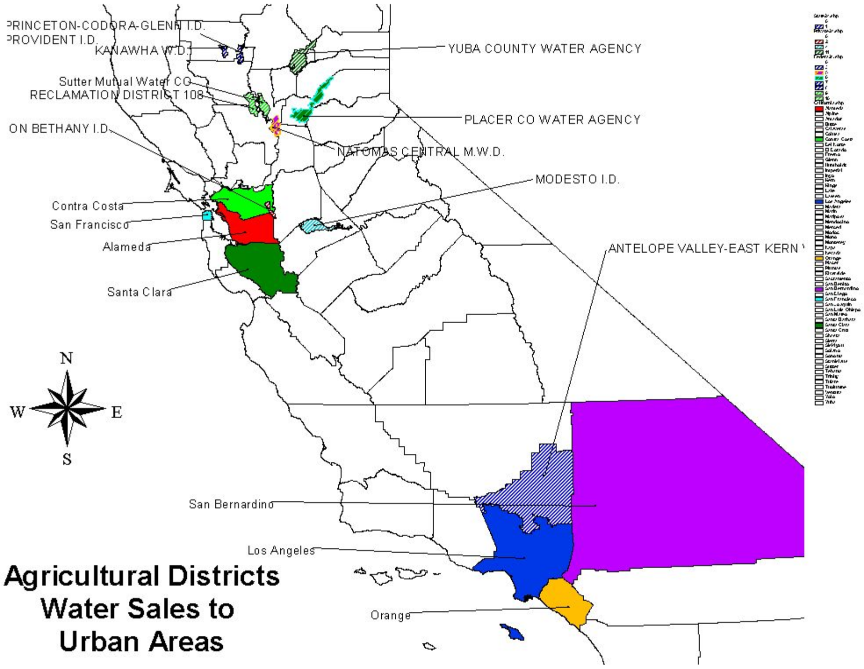

Figure 2-5. Districts Involved in Water Transfers to Urban Areas

Many more districts (57% of the researchers' current list, which does not include some districts) have sold water to other agricultural districts, but the sales of water in this case are virtually all short-term sales. Researchers suspect these short-term sales are more in the category of trades between neighbors rather than sales that would support an open and well functioning water market. Figure 2-6 shows the frequency of California water transfers between 1985 and 2000.

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[4] This database includes information only on sales by agricultural water district, and the county of the buyer.

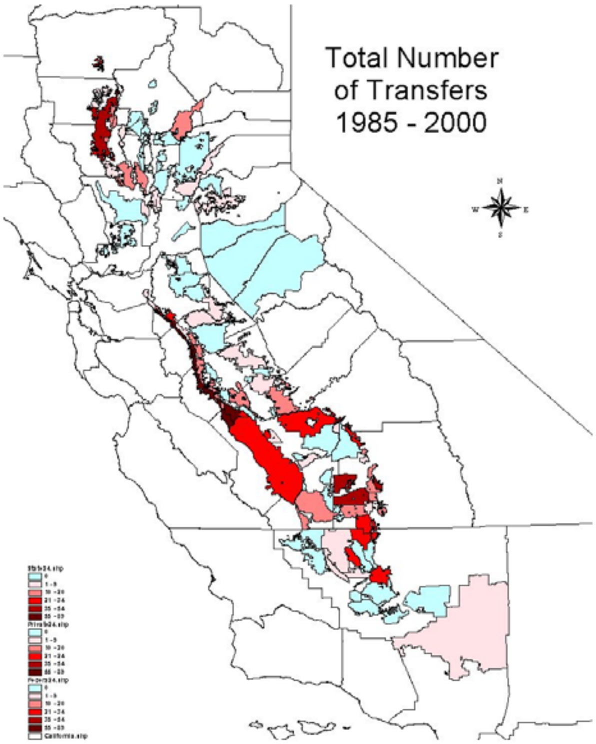

Figure 2-6. Frequency of Water Transfers

The plan is to analyze the economic and political factors that influence a district's decision to sell water. This analysis will test a number of hypotheses raised in the technology adoption and market adoption literature. These include rigid short-run farm production technologies, lack of sufficient conveyance infrastructure, transactions costs, third-party impacts, and political and legal risk.

Markets for tradable emissions permits are the economically preferred tool for reducing pollutants such as GHG. Researchers will conduct an assessment of the performance of existing markets of this type (including GHG, SO_2, Tradable Fish Permits) with the goal of drawing lessons for their potential application in California water; proposing to synthesize and apply the lessons drawn from this literature to begin practical design of California-based and/or regional markets for water.

2.2. Cropping Patterns

The Regional Offices of the DWR perform land surveys of every field in the Central Valley every two or three years. These surveys indicate an incredible diversity of Central Valley agriculture, including high-value fruit and vegetable crops and low-value field crops and cotton.

Crop data from the GIS dataset for the San Joaquin Valley illustrates the distribution of high- and low-value crops, as shown in Figure 2-7. Although most crops may be grown in almost any part of the Central Valley, high-value crops tend to predominate in the east side of the San Joaquin Valley. Comparing this information to the water delivery data, it appears that the high-value cropping occurs primarily in areas with better access to surface water deliveries.

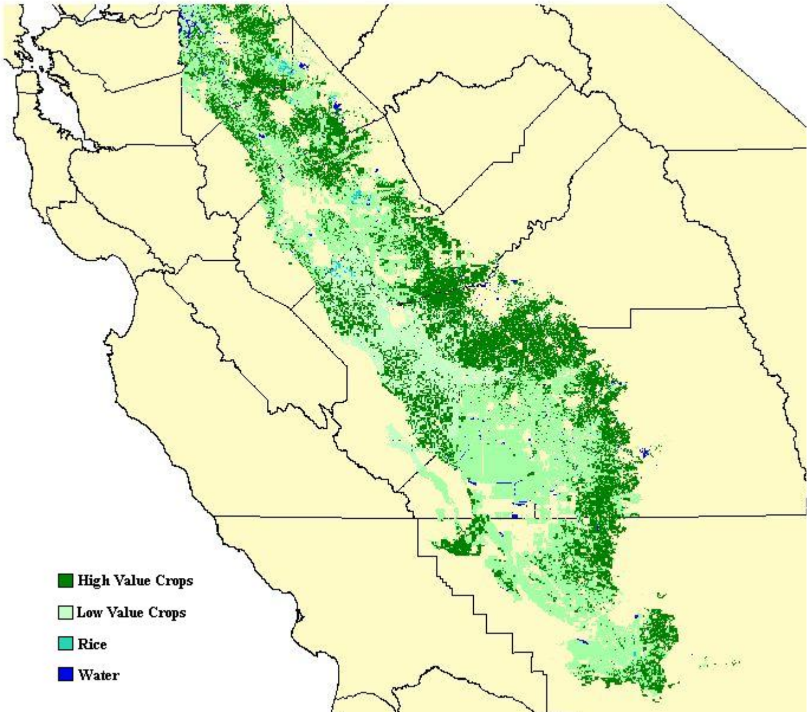

Figure 2-7. San Joaquin Valley Cropping Patterns

2.3. Agricultural Land Values

The database of farmland value for this study was derived from the USDA June Agricultural Survey. This survey is conducted in June of each year to construct forecasts of expected yields of most crops. The survey includes a random sample of the Census of Agriculture and a stratified sample of farms based on geographic location. The stratified sample is geo-referenced by latitude and longitude.

The sample includes self-reported farmland value per acre for the years 1998–2003. The distribution of farmland values (in year 2000 values) reported in the survey for the California Central Valley is shown in Figure 2-8.

Similar to water supply data, farmland values vary widely across the Valley, but tend to be highest in districts located in the central and eastern portions of the Central Valley (Figure 2-8).

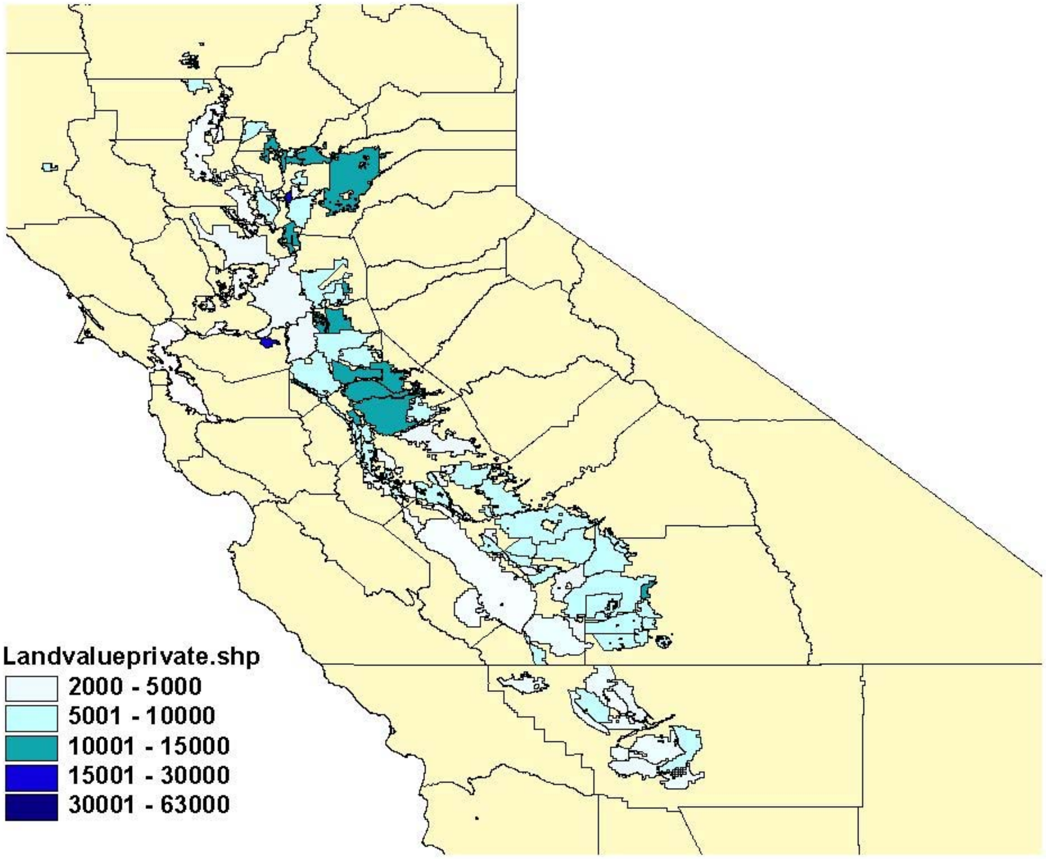

Figure 2-8. Agricultural Land Values Reported in Central Valley Water Districts (dollars per acre)

3. The Value of Water Supply Reliability to California Agriculture: A Preliminary Analysis

3.1 Introduction

This section examines the potential damage to California agriculture from predicted changes in water supply reliability under climate change. Researchers compiled a unique micro-level dataset of farms in California that allows them to test how different water rights capitalize into farmland values. These capitalized values are hence the implicit market prices for the water rights of the land. Although there have been theoretical studies that outlined the value of varying water rights with different seniority in the Southwest (Burness and Quirk 1979; Burness and Quirk 1980), there are only a few empirical studies that have examined whether and how access to irrigation water is capitalized into farmland value in practice. Hartman and Anderson (1962) consider land sales within an irrigation district in Colorado; and Crouter (1987) considers land sales within a different irrigation district in Colorado; Faux and Perry (1999) consider land sales in four irrigation districts in Malheur County, Oregon. Finally, Moreno et al. 2005 evaluate agricultural land values in a single water district in California. Three of these studies find that water availability is a significant determinant of farmland value. However, all four studies cover a much smaller area than this study's sample, which extends to over 150 irrigation districts in 39 counties in California. This study's larger spatial coverage permits us to allow for the effect on farmland value of climate variables that are not likely to vary much within the small scale covered by these other studies. The only other study that incorporated surface water use on a larger scale relied on average farmland values in a county, where both dryland and irrigated farmland values are averaged (Mendelsohn and Dinar 2003).

The analysis proceeds as follows. Section 2 discusses the history of water projects in California that motivate the study, Section 3 introduces the reduced form hedonic model, Section 4 describes the unique dataset, Section 5 describes and discusses the study's empirical results, Section 6 provides a sample calculation of the potential impact of climate change on farmland value, and Section 7 presents the conclusions.

3.2 Background: Irrigation in California

At the beginning of the twentieth century, California was still very much an agricultural state. Under appropriative water rights, users could file a claim for water rights with the SWRCB, as long as the water was put to a beneficial use. Water rights are a prime example of first-order stochastic dominance: because the runoff of rivers is stochastic, individual water rights are filled by seniority (i.e., the first claimant has the right to receive his or her entitlement first). With decreasing seniority, each claimant can only get water from the remaining water resources after the entitlements of more senior water right holders have been satisfied. The random nature of water availability was exacerbated by the fact that limited storage capacity was available at the beginning of the twentieth century. Precipitation occurs almost exclusively during the winter and in the northern part of the state, therefore, storage and conveyance facilities are necessary to bring surface runoff to the south and to farms during the growing season. In sharp contrast, the use of groundwater is virtually unregulated, which, similar to all common access problems, gives a disincentive to conserve the groundwater table for future periods.

About one-and-a-half million acres were under irrigation in the San Joaquin Valley by 1930 and almost all of them relied on groundwater as the source of irrigation (Reisner 1986). However, extensive overdraft of the unregulated groundwater resources had resulted in a drop of the water table of as much as 300 feet. There was heightened concern that accessible groundwater would vanish in the next couple of decades. In 1933 the state legislature approved the Central Valley Project (CVP), which was designed to capture two thirds of the state's runoff. Almost all of the water that is captured in the Sierra Nevada is collected in the Sacramento River (Northern California) and the San Joaquin River (Southern California) which meet at the Delta and empty into the ocean. The CVP collects water from these river basins, and transports it from the northern part of the state to the southern part for several hundred miles through canals and by reversing the natural flow of some rivers.

When voters finally approved a $170 million bond measure to build the project, the country was in the Great Depression and the State of California was not able to sell the bonds. President Franklin Roosevelt ordered the U.S. Bureau of Reclamation to take over the project in December 1935. The original project was constructed between 1937 and 1951, with several newer features being added later. By 1990, the CVP had 20 dams and reservoirs capable of storing 12 million acre-feet (MAF) of water and 500 miles of major aqueducts and canals. The three largest dams are Shasta Lake, with a capacity of 4.5 MAF (completed in 1945), Clair Engle Lake (completed in 1962), and New Melones Reservoir (completed in 1979), with storage capacities of about 2.5 MAF each. Water that would otherwise flow into the Delta is pumped into the Delta Mendota Canal at the Tracy pumping plant. The pumping capacity of this plant is 6.34 acre-feet per minute. The total annual contracting quantity of the CVP is 9.3 MAF, where 4.8 MAF are project water and 4.5 MAF are water rights settlements (i.e., deliveries to contractors with water rights dating back before the project was built who hence have the highest seniority to get water from the rivers that now feed the CVP).

The growing urban demand for water in Southern California led to the construction of another large surface water storage and distribution system that is owned by the State of California–the California State Water Project (SWP) with yearly contracts averaging 4.2 MAF of water. The SWP consists of 22 dams and reservoirs, by far the biggest of which is Oroville Dam with a storage capacity of 3.5 MAF. The SWP was constructed between 1961 and 1973 and delivers about 2.5 MAF of water to Southern California, depending on wetness conditions. It also supplies water to irrigation districts, (about 1.3 MAF in the San Joaquin Valley). These water deliveries are not subsidized and the wholesale cost in Kern County is about $70/AF. The SWP has only about 60% of the supply capacity that was originally planned in 1960. Completion of the remainder has been blocked since 1982, when voters rejected Proposition 9 to build the Peripheral Canal.[5] If the system were now to be built out, current estimates are that the new

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[5] Proposition 9 proposed the construction of a peripheral canal to transport additional water diversions from Northern California rivers to Southern California *around* the San Francisco Delta rather than transporting water through the Delta using the natural river channels, which was environmentally damaging. The proposition's defeat killed prospects for additional water transfers.

water storage facilities would cost on the order of $500–$1,000/AF (California Department of Water Resources 1998; Frederick and Schwarz 2000), which is much larger than historic cost estimates and hence historic water rights result in rents for farmers. Continued conflict and expensive legal battles over water rights demonstrate that these rents must be of significant magnitude. One would hence expect that that these rents capitalize into farmland values. The next section presents a brief model to motivate the reduced form analysis used to estimate how water rights capitalize into farmland values.

3.3 Model

This sections sketches out the model for the reader. The model defined profits p from planting crop k in farm i in location j equal to:

$$p_{i,j,k} = p_k(p_k, w_{i,j}, z_{i,j}) - C_{i,j,k}$$

In this case, p is a vector of prices; w is input cost; z represents other farm data; C is fixed cost.

In the model, farmland value equals the present value of discounted profits (where q is capitalization ratio). In this case, farmland value may be defined as:

$$V_{i,j,k} = V_{i,j,k} + x_{i,j,k} = pq_k(p_k, w_{i,j}, z_{i,j}) - qC_{i,j,k} + x_{i,j,k}$$

The error composition model in this formulation is:

$$x_{i,j,k} = e_{i,j} + n_j + j_k$$

Researchers assume farmers plant their most profitable crop, so that

$$V(p, w_{i,j}, z_{i,j}) = \max\{ V_1(p_1, w_{i,j}, z_{i,j}, C_{i,j,1}) + x_{i,j,1} , \ldots , V_K(p_K, w_{i,j}, z_{i,j}, C_{1,j,K}) + x_{1,j,K}\}$$

If all j_k have extreme value distribution then

$$\begin{aligned} E[V(p, w_{i,j}, z_{i,j})] &= \ln[\ S_k \exp(V_k(p_1, w_{i,j}, z_{i,j}, C_{i,j,k}) + e_{i,j} + n_j)\ ] + 0.57722 \\ &= \ln[\ S_k \exp(V_k(p_1, w_{i,j}, z_{i,j}, C_{i,j,k})\ )\ ] + e_{i,j} + n_j + 0.57722 \end{aligned}$$

This allows an approximation of outer envelope:

$$V_{i,j} = x_{i,j}' b + e_{i,j} + n_j$$

This analysis allows for a non-diagonal variance-covariance matrix such that there is spatial correlation of the error terms. It also assumes a random effects model (both in sampling locations and water districts).

3.4 Data

3.4.1 Dependent Variable

The dependent variable, farmland value per acre, was derived from the June Agricultural Survey (National Agricultural Statistics Service 2004). This survey is conducted in June of each year to construct forecasts of expected yields of most crops. The survey is split into two parts: the first is a random sample of the Census of Agriculture, while the second is a stratified sample of farms based on geographic location. This study relies on the second part, as it is a geo-referenced sample of all farms (i.e., USDA randomly selects latitude and longitude combinations and records all farms in the immediate vicinity).

The hedonic regression uses the self-reported farmland value per acre as the dependent variable. The dataset includes observations for the years 1998–2003, and all farmland prices were adjusted by the gross domestic product (GDP) implicit price deflator to be in 2000 dollars. Figure 3-1 illustrates the locations of farmland values reported in the survey. The study assumes that self-reported farmland values are correlated with market farmland values. In the future, the researchers will attempt to test this assumption by gathering other farmland value data sources.

3.4.2 Exogenous Variables

This study uses a 103-year, high-resolution temperature and precipitation climate dataset for the coterminous United States. This small-scale climate series was developed by Spatial Climate Analysis Service at Oregon State University for the National Oceanic and Atmospheric Administration (NOAA). Researchers at Oregon State University developed the PRISM model that is employed by almost all professional weather services and regarded as one of the most reliable interpolation procedures for climatic data on a small scale.[6]

The existing economics literature has generally represented the effect of climate on agriculture by using the monthly averages for January, April, July, and October. However, from an

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[6] This study’s PRISM run gives monthly minimum and maximum temperature values and precipitation estimates on a 2.5-mile x 2.5-mile grid for the contiguous United States.

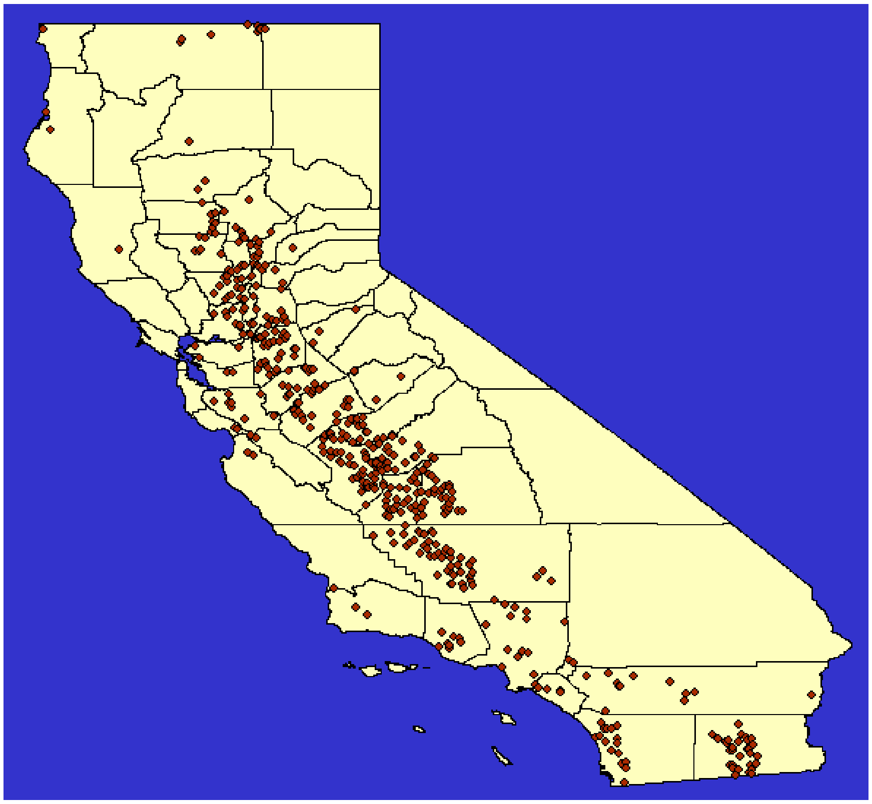

Figure 3-1. Sample Locations in California

agronomic perspective, this approach is less than optimal. First, except for winter wheat, most field crops are not in the ground in January; most are planted in April or May and harvested in September or October. Second, plant growth depends on exposure to moisture and heat throughout the growing season, albeit in different ways at different periods in the plant's life cycle; therefore, including weather variables for April and July (but not May, June, August, or September) can produce a distorted representation of how crops respond to ambient weather conditions. The agronomic literature typically represents the effects of temperature on plant growth in terms of cumulative exposure to heat, while recognizing that plant growth is, in part, a nonlinear function of temperature. Agronomists postulate that plant growth is a linear function of temperature only within a certain range, between specific lower and upper thresholds; there is a plateau at the upper threshold beyond which higher temperatures become harmful.[7] This agronomic relationship is captured through the concept of *degree-days,* defined as the sum of degrees above a lower baseline and below an upper threshold during the growing season. Here, the study followed the definition of Ritchie and NeSmith (1991) and set the lower bound equal to 8°C (46°F) and the upper bound to 32°C (90°F).[8] In other words, a day with a temperature below 8°C (46°F) results in zero degree-days; a day with a temperature between 8°C (46°F) and 32°C (90°F) contributes the number of degrees above 8°C (46°F); and a day with

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[7] In addition to temperature per se, plant growth is influenced by solar radiation. However, data on solar radiation are relatively sparse and, at this point, it has not been possible to obtain sufficient data to include this variable in our regression analysis.

[8] Ritchie and NeSmith (1991) mention that some researchers have suggested a lower bound of 6°C (43°F); in our empirical analysis, we also experimented with using this lower bound and we found that, as is to be expected, it increases the estimated optimal number of degree days.

a temperature above 32°C (90°F) contributes 24°C (75°F) degree-days. Degree-days are then summed over all days in the growing season. Researchers derived the sum of degree-days during the main growing season (i.e., for the months of April through August using the 50-year temperature averages between 1948–1997).

Boundaries of all major irrigation districts were obtained from the DWR, which made it possible to link individual farms to irrigation districts. Water deliveries of the CVP between the years 1992 and 2002 are available in the Operations Report from the CVP and DWR Bulletin 132.[9] Researchers matched this data with estimated water deliveries and water prices obtained from ACWA. It should be noted that the available data on water rights in California are often incomplete, and it is not easy to obtain comprehensive and accurate information about water rights. Researchers are still in the process of expanding and updating the database on water rights. Historic water prices over the last 50 years for water deliveries from the Central Valley Project are listed in the 2000 Irrigation Water Rates Manual available at the library of the Bureau of Reclamation in Sacramento. Finally, the acreage of each district is derived with the help of geographic information systems of the irrigation district boundaries.

Researchers also obtained observations on more than 15,000 groundwater wells in the Central Valley. Groundwater is a virtually unregulated resource and in many areas it provides a substitute for surface water in the event of a shortage. The depth of groundwater varies significantly, both spatially and temporally, between years and between months within a year. Researchers calculated the average well depth in the month of March, the beginning of the growing season, for each of the years 1990 to 1998 and then averaged the depths over these years. The groundwater depth at each farm location is derived as a weighted average of all well locations, where the weight is the inverse of the distance of each well to the farm to the power of 2.14—the exponent that minimizes the sum of prediction errors from cross-validation. In the cross-validation step each well is excluded from the data at a time and the depth is calculated using all remaining wells. The square of the difference between interpolated depth and actual depth are summed over all well locations.

There are several soil databases of potential interest to this analysis. In order of increasing detail, they are the: (i) National Soil Geographic (NATSGO) Database that relies on the National Resource Inventory (United States Department of Agriculture 2000), (ii) State Soil Geographic (STATSGO) Database (United States Department of Agriculture 1994) and (iii) Soil Survey Geographic (SURGO) Database (United States Department of Agriculture 1995). While SURGO is the most detailed soil database designed to allow erosion management of individual plots,

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[9] This analysis limits our sample to years after 1992 when the Central Valley Improvement Act was passed that allocated more water to instream environmental uses and limited the amount of water that can be exported at the pumping plants in the Delta. However, we also conducted an analysis using average deliveries between the years 1982–2002 and found little difference in the results. It should be noted that the water delivery data are an ex post measure of surface water availability. In future work, we intend to include an estimate of the irrigation districts' ex ante expectations, as of the time of crop planting, regarding how much water will be available for delivery during the balance of the growing season.

there is no uniform reporting requirement for the United States. Furthermore, the observations in the June Agricultural Survey include all farms in the vicinity of a longitude/latitude pair, and hence, choosing field characteristics of one individual plot appears inappropriate. Instead, the study uses the more aggregated soil database STATSGO, which groups similar soils into polygons for the entire United States. Average soil qualities are given for each polygon. Although this soil database gives a first approximation of the actual average soil qualities, there might be significant heterogeneity, which is addressed in the empirical section.

Finally, farmland close to urban areas has an inflated value compared to farmland elsewhere because of the option value of the land for urban development (and also, perhaps, because of superior access to urban consumers). Plantinga et al. (2002) examine the effects of potential land development on farmland prices and find that a large share of farmland value, more than 80% in major metropolitan areas, is attributable to the option to develop the land for urban uses. This study therefore constructed a variable to approximate population pressure by summing the population in each of the 7049 Census Tracts from the 2000 Census (U.S. Census Bureau 2002) divided by the inverted square of the distance of the tract to the farm. Table 3-1 displays the data’s summary statistics.

Table 3-1. Descriptive Statistics

Variable	Mean	Min	Max	σ
Thousand Degree Days (8°C–32°C) April–August	2.08	0.75	3.08	0.37
Preceipitation March–August (Feet)	0.33	0.06	1.8	0.19
Percent Clay (Percentage Points)	23.37	2.48	51.29	10.55
K-Factor of Top Layer (times 100)	30.37	10.82	45.67	5.48
Minimum Permeability of All Layers (Inches / Hour)	1.39	0	13.7	1.97
Average Water Capacity (Inches / Inch)	7.4	1.46	21.99	2.7
Percent High Class Soil (Percentage Points)	45.25	0	100	31.49
Population Density (People / Distance Squared / 1000)	8.71	0.29	111.85	8.62
Depth to Groundwater (Feet)	65.27	7.88	252.89	38.16
Federal + Private Water (Acre-Feet / Acre)	0.72	0	4.63	1.12

3.5 Empirical Analysis

This section presents the estimates for the hedonic regression with farmland value per acre as the dependent variable. The results are listed in Table 3-2. The table uses feasible generalized least squares (GLS) weights that account for the spatial correlation of the error terms.[10]

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[10] If two observations were recorded at the same location, researchers assigned a distance of 1 mile, as by construction the June Agricultural Survey samples all farms within 1 mile.

Researchers conducted three spatial tests to test whether spatial correlation is indeed a problem. One test is the Moran-I statistic (Anselin 1988). However, since this test does not have a clear alternative hypothesis, researchers supplemented it with two Lagrange-Multiplier tests involving an alternative of spatial dependence: the LM-ERR test of Burridge (1980) and LM-EL test of Anselin et al. (1996).[11] The normal test statistic for the Moran-I is 16.8, and the Lagrangian multiplier test are $\chi^2(1)$-distributed with test statistics of 299 and 289, respectively. Therefore, all tests indicate that spatial correlation is indeed present. Hence the standard ordinary least squares (OLS) estimate underestimates the true variance-covariance matrix—OLS assumes all errors to be independent, even though they are in fact correlated. This suggests that standard OLS estimates of standard errors for hedonic regression equations generally might be misleading if the error terms among observations in close proximity are correlated. In fact, it is not uncommon in hedonic studies for variables to be statistically significant, yet to switch signs between alternative formulations of the model. Table 3-2 therefore uses feasible GLS to construct the most efficient estimator by premultiplying the data by $(I - \hat{\rho}W)$. In the second stage, researchers estimated the model and use White's heteroscedasticity consistent estimator to account for the heteroscedasticity of the error terms (White 1980).

The estimates in Table 3-2 are based on observations with a farmland value below $20,000 per acre and water prices below $20. Including higher value observations in the analysis increases the R-square of the regression, but the variable with the greatest explanatory power becomes population density. At the same time, the confidence levels for soil quality and water availability are reduced. Farmland with values above $20,000 per acre is generally close to urban areas, and the value of this land reflects what is happening in the urban land market, and the value of the future potential to develop this land for urban use—not what is going on in the local agricultural economy. Including these observations creates large outliers and results in estimates that are mainly driven by these outliers.[12]

Second, the research team excluded irrigation districts with expensive water prices from the analysis to get a better estimate of the net value of water. Only the net value of water, the difference between gross value and delivery cost (including price) capitalizes into farmland values. As an example, if the gross discounted value of an acre-foot of water were $1000 and the annual delivery cost $50, the net value of the water would be zero (using a discount rate of 5%). The researchers therefore test the sensitivity of the results to variations in water price by excluding irrigation districts with high prices from the analysis to get a better estimate of the net value of water.

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[11] See Anselin and Florax (1995).

[12] The researchers also experimented with using median regression to estimate the hedonic farmland value equation and found that this produced similar results, which were very stable and almost insensitive to the cutoff point.

Table 3-2. Hedonic Regression of Farmland Value ($ per acre)

Variable	Coeffcient	t-Value
Constant	7670	-2.88
Degree Days (8°C− 32°C) April-August	2514	-1.31
Degree Days (8°C−32◦C) April-August Squared	-771	-1.85
Precipitation March−August	3108	-1.56
Precipitation March−August Squared	-1140	-1.19
Percent Clay	-49.4	-4.15
K-Factor of Top Layer	-66.1	-3.41
Minimum Permeability of All Layers	-129	-1.65
Average Water Capacity	-186	-3.92
Percent High Class Soil	8.56	-2.98
Population Density	82.9	-4.2
Depth to Groundwater	-1.55	-0.66
Federal and Private Water Availability	809	-8.78

Number of observations 2758 R-square (standard OLS) 0.18

All observations where the farmland value is in excess of $20,000 were excluded, as well as observations with water prices above $20.

See later sections for a sensitivity analysis for different cutoff points.

The coefficients on the climatic variables appear reasonable. The result for degree-days implies that the quadratic form peaks at 1630 degree-days. This is consistent with the agronomic literature, which indicates degree-day requirements of this order of magnitude for several important crops grown in the Central Valley.[13] While the coefficients are borderline significant under the feasible GLS model, the p-value on the hypothesis that the linear and squared term on degree-days is jointly equal to zero is 0.008, and degree-days as a group are hence highly significant. One potential problem in the estimation using both the linear and squared variable is the high degree of colinearity between the two variables, which will reduce the significance level of each *individual* variable. The correlation coefficient between degree-days and degree-days squared is 0.98. Another problem is that the variation in climatic variables with the Central Valley, the main growing region, is limited. In a related paper that examines the effect of degree-days on farmland values in the Eastern United States, the degree-days variables are comparable in size and highly significant. Because many tree crops need cool nights, increasing

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[13] The degree-day requirement for rice is 1350 degree-days, corn is 1300–1500 degree-days, and grapes are 1700 degree-days, while cotton is approximately 1700–1900 degree-days.

temperatures substantially above the required degree-days to grow a crop can only be harmful.

The sign of the regression coefficient on water availability in Table 3-2 makes intuitive sense: rights to subsidized surface water are beneficial. However, water rights have a price, as well as a quantity dimension. As mentioned before, only the net value of water capitalizes into farmland values. Therefore, the study tested the sensitivity of its results to variations in water price by excluding irrigation districts with high prices from the analysis, to get a better estimate of the net value of water. Restricting the sample to observations that have water rights with water prices less than \$30, \$40, and \$50, and using no price restriction at all decreases the value of an acre-foot from \$809 in Table 3-2 to \$625, \$583, \$524, and \$395, respectively, as the hedonic regression only picks up the net benefit of the water right.

The linearity of the coefficient on water rights is confirmed when dummies for different ranges of water rights are included.[14] The sample includes districts with zero private or federal water rights. These are districts that depend primarily on groundwater and state water. Since state water is very expensive, it is excluded from the estimation.[15] Finally, a greater depth to groundwater is harmful, as it would result in larger pumping costs, but the coefficient of this variable is not significant.

Soil variables have intuitive signs as well, and four of the five soil variables are significant at the 5% level. Higher values of the variable K-factor indicate increasing erodibility of the top soil. Similarly, a higher clay content is also less desirable, as is low permeability, which indicates a soil that does not hold water. Finally, population density has a big influence on land prices: this variable is highly significant and of a large magnitude compared to the sample mean. The potential to sell agricultural land for urban development is often the most profitable option for farmers.

The research team conducted several sensitivity checks, which are listed in Appendix 1. The results on water availability are remarkably robust, while the results for the variable degree-days are more sensitive to the particular implementation. However, the latter might be

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[14] The sample was restricted to districts that pay less than \$20 per acre-foot, to single out the effect that is due to quantity, not price. The research team replaced the actual quantity by dummies for districts with water rights in the range $(0, 1]$, $(1, 2]$, $(2, 3.5]$, $(3.5, 5]$, and $(5, \infty)$ acre-foot per acre, and the resulting coefficients are \$696, \$1864, \$2332, \$3544, \$-1872 respectively. The first four are line with an estimate of \$809 per acre-foot per acre, while the last one is clearly not. However, Glenn-Colusa Irrigation District is the only district that has more than 5 acre-feet per acre in our sample, and hence, some unique feature of this district is being picked up with the dummy variable. When researchers checked the sensitivity of the results to including/excluding a single district at a time, the only one with a large impact was Glenn-Colusa. They therefore excluded the district from the analysis, as they feared that it was misreported.

[15] It is very difficult to obtain reliable quantitative data on surface water rights for many agricultural water users in California, as different sources often give conflicting estimates of these water rights. The research team is still in the process of updating their data on individual water rights with a view to extending the present analysis in future research.

explained by the limited climatic variation in this project's sample study. The team conducted a similar analysis for the Eastern United States (all counties east of the 100 degree meridian) with much larger variation in climatic variables, and find results that are again very robust and similar to the ones presented above.

3.6 Predicted Climate Change Impacts

The coefficients on the climatic variables can now be used to calculate the impact of climate change on farmland values in California. The impact of climate change on farmland values can be derived by evaluating the hedonic function both at the current climate and at a new predicted climate.[16] First, note that a decrease in availability of federal and surface water would have a large and significant impact on the value of farmland. The coefficient on water availability is between \$400–\$850 per AF, depending on the price a district pays for water.[17] Because researchers modeled surface water availability as additively separable from other exogenous variables, the impact is easily derived as the product of the value per AF and the decrease in water availability.[18]

As mentioned before, recent hydrological studies for moderate-temperate climates utilizing a smaller geographic scale discovered that despite the increase in annual precipitation, the runoff during the main growing season (i.e., between April and September), might actually decrease as a seasonality effect dominates the annual effect.[19] The decrease in runoff translates into decreasing surface water availability, where the magnitude depends on the seniority of water rights. More senior water rights holders always get served first and are hence less prone to a decrease in water availability. For the same reason, junior rights holders will face potentially large reductions in availability. Given that the estimated value for cheap water is \$809 per AF, a

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[16] The hedonic approach is a partial equilibrium approach and hence assumes constant prices. However, recent agronomic studies predict that world production might not be affected significantly, but climate change will create regional winners and losers. Such a scenario would have limited impacts on world prices.

[17] The value of \$500 is an upper bound on expensive water, as we pool cheap and expensive water. If a farm were charged the marginal value of water, water rights would have zero net value.

[18] Researchers also included cross terms between water availability and other exogenous variables, but none of them were significant.

[19] The recent U.S. Assessment Report on agriculture (Reilly 2002) tended to overlook the issue of precipitation timing. Most water use in U.S. agriculture occurs during the spring and summer, so that an increase in winter precipitation does not, per se, increase the effective water supply for agriculture. In principle, it is possible to develop more storage to capture the extra precipitation, but that has an economic cost that was not considered by the Assessment Report.

modest reduction of just 0.5 AF per acre will lower the value of the affected farmland by approximately $400 per acre.

In this study's degree-day model, changes in temperatures have nonlinear effects on the resulting number of degree-days. In fact, the study's approach is conservative in the sense that temperatures above the upper threshold $b2 = 32°C$ (90°F) are assumed to have no impact on plant growth (i.e., the number of degree-days for 32°C (90°F) and 35°C (95°F) are the same). The approach therefore assumes the marginal effect of further temperature increases to be zero, while some agronomic studies argue it should be negative.[20]

Table 3-3 lists the average area-weighted impact of a change in climatic conditions for three uniform temperature increases.[21] The research team used the coefficient estimates from Table 3-2 that corrects for the spatial correlation of the error terms.[22]

Table 3-3. Average Impact of Different Uniform Increases in Temperature on Farm Values ($ per acre)

	+1◦ C	+2◦ C	+3◦ C
Impact in $ per acre	-107	-284	-482
Significance (t-value)	-1.29	-2.09	-2.57

For comparison, the area-weighted value of all observations in this study's sample is $4,265. On average, the value of farmland in California would decrease by $482 per acre, or around 11%, under the hottest 3°C (5.4°F) increase scenario. However, the distribution of impacts is quite different, ranging from large damages to modest benefits. Existing areas with a very hot climate—especially farms in the Imperial Valley—would face much larger relative decreases in value, while farmland around the Delta with its natural cooling mechanism would benefit slightly from an increase in temperatures, and hence degree-days. Given the linear structure of the hedonic equation, the aggregate impact is simply a linear combination of the regression coefficients, and hence is itself normally distributed. One can therefore calculate the significance levels for the test of whether the aggregate impact is significantly different from zero. The

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[20] Most field experiments examine growth if temperatures exceed a certain threshold but do not allow for increased supply of water. Under such circumstances an increase in temperature will definitely be harmful.

[21] These uniform increases should be regarded as straw man climate change scenarios, in the spirit of Mendelsohn, Nordhaus, and Shaw (1994). In future work, this research will employ general circulation model (GCM) predictions downscaled to California, such as those recently published by Hayhoe et al. (2004).

[22] Note that, in using these coefficient estimates, we are assuming that the historical relationship between growing degree days and agricultural production will continue to hold in the future. This might not happen because of changes, for example, in the diurnal temperature profile of daytime versus nighttime temperature, or in solar radiation.

t-values suggest that the impact becomes significant around 2°C (3.6°F). Using the classification of IPCC, the study found that a negative impact is *very likely* for the +2°C (+3.6°F) and +3°C (+5.4°F) scenarios.

As pointed out above, the coefficient on the degree-days variables are less robust, however, similar results are obtained in a comparable study covering a larger geographical and climatic range gives comparable results. At the same time, the potential decrease in water availability appears to more damaging, especially for junior holders.

4. Conclusions

This analysis studies how climatic variables and the access to subsidized surface water capitalize into farmland values, and how these values would be affected by changes in the climatic variables. Using a micro-level data set of individual farms in California researchers examined how degree-days, a non-linear transformation of temperature variables, and related changes in water availability, capitalize into farmland values.

This study found that the standard OLS approach underestimates the true variance-covariance matrix of the estimator and therefore overestimates the significance of the regression coefficients, including those on the climate variables, because it incorrectly assumes that observations are identically and independently distributed. Nevertheless, the estimates of the impact of a change in water availability remain highly significant, even when allowing for spatial correlation or including random effects, though the significance is of course reduced relative to OLS.

Similarly, coefficients on the linear and quadratic degree-days variables are in line with what one would expect from agronomic studies, but the estimates seem less robust to the inclusion or exclusion of non-climatic control variables. Researchers note also that the limited temperature variation in the study area makes estimation of the effect of temperature or degree-days on farmland value somewhat problematic. The team has conducted a similar analysis for the eastern United States and found that extending this analysis to a larger area characterized by greater variation in temperature gives highly significant degree-days coefficients that are comparable in magnitude to the ones presented here.

The average magnitude of the impact of a potential decrease in water availability on farmland value appears to be larger than the one caused by an increase in temperature, because a decrease in water availability is harmful for all farms in California—a state that crucially depends on irrigation. On the other hand, the effect of an increase in temperature is mixed, ranging from modest benefits of an increase in temperature to potentially large damages in the Imperial Valley.

Several caveats apply to this analysis. Perhaps the most important is that data on water rights is difficult to obtain, and the research team is continuing to develop finer and more accurate measures that might change the coefficient estimates. Moreover, the team's current measure of water supply uses average annual historical deliveries; in future work, they will include measures of supply reliability that reflect the uncertainty facing water districts each spring, at the time cropping decisions are made. In addition, since the analysis relies on cross-sectional data it does not pick up any potential changes not reflected in the data, most notably changes in prices, technology, CO_2 fertilization, or the potential reduced water-requirements through CO_2 fertilization.

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Appendix A. Sensitivity Checks

Hedonic regressions are prone to misspecification and the influence of outliers. We therefore present the results of further robustness checks.

A-1. Random Effects and Fixed Effects Model

The above analysis incorporates the spatial correlation of the error terms. However, as pointed out in the data section, all farms within a one-mile circle are sampled in the June Agricultural Survey, and hence the error terms in a particular location might be correlated. Moulton (1986) points out that treating grouped data as independent can underestimate the true variance-covariance matrix. One of his examples is a hedonic regression study of housing in the greater Boston area where he finds that standard OLS variance-covariance matrix underestimates the true variance-covariance matrix by a factor of between 1.3 and 2.4. The effect of the understatement of the variance-covariance matrix is to overstate the significance of the regression coefficients. We therefore estimate two random coefficient models where we cluster both by sampling location and by the irrigation district. Furthermore, we include county fixed effects to at least partially capture differences in seniority of water rights as farms on the east side of the Valley traditionally have more senior rights. County fixed effects force the identification to come solely from the variation in water rights within a county. The coefficient on the variable water rights decreases slightly to 660 but remains highly significant with a t-value of 3.67 and 2.99 when we cluster by sampling location and irrigation district, respectively. On the other hand, the coefficients on the climatic variables become insignificant. This is not surprising as there is very limited variation in climate within a county, and hence these variables are only identified by comparing farms in different counties, but these differences are absorbed in the fixed effects. There are, however, farms with significant variation in water availability within a county that identify the coefficient on surface water availability.

A-2. Median Regression

In order to examine the influence of individual observations we replicate the analysis using median regression. In a median regression one minimizes the sum of absolute deviations instead of the sum of squared deviations under OLS, hence giving much less weight to outliers. The coefficient estimates under median regression remain robust. More specifically, the coefficient on federal and private water surface water availability increases to 1018. We use 10,000 model-free bootstrap simulations to estimate the variance-covariance matrix.[23] The t-values are 6.16 and 5.73 when we cluster by sampling location and irrigation district, respectively.

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23 We incorporate the grouped structure of our data by first sampling groups and then drawing random samples from within each group.

A-3. Extreme Error Bound Analysis

In a third step, using an approach suggested by Leamer (1983) we estimate the robustness of our results to varying modeling assumptions by taking permutations of our set of independent variables. While it is somewhat ad hoc to rerun models with all possible combinations of the independent variables, this sensitivity analysis, presented in Table A-1, indicates that our main estimates are robust across different modeling assumptions. Specifically, we use three sets of permutations: (i) all possible combinations of the five soil variables; (ii) soil variables as well as the location-specific variables population density, and depth to groundwater; (iii) all variables of (ii) plus precipitation and the other variable of interest, i.e., either degree days or water availability. Since we allow each of the n variables under consideration to be included or excluded in the model, there are 2^n possible combinations. The results of the possible combinations on our variables of interest (the optimal number of degree days, i.e., where the quadratic term peaks; as well as the coefficient on federal and private surface water availability) are given in Table A-1.

Table A-1: Sensitivity of Coefficient Estimates to Different Model Specifications

Variables	**Models**	**Mean**	**Minimum**	**Maximum**	**Std. Dev.**
Soil Variables	32	875	826	911	24.5
Soil + Location Variables	256	851	716	952	56.4
Soil + Location + Climate	4048	907	716	1043	54.4

The soil variables are (i) Percent Clay, (ii) K-Factor of Top Layer, (iii) Minimum Permeability, (iv) Average Water Capacity, and (v) Percent High Class Soil.
The location variables are (i) Population Density (including squared term),
(II) Depth to Groundwater. The other variables are precipitation and degree days days variables (including squared terms) when the sensitivity of the water coeffcient is tested; and Precipitation (including squared term); and water avilability when the sensitivity of the degree days variable is tested.

Note that all coefficients in the Table are calculated using standard OLS, while Table 3-2 uses feasible GLS weights. However, the latter repeatedly requires one to calculate an inverse of a 3000x3000 matrix and is hence very computer intensive. We therefore revert to standard OLS which will give an unbiased estimator, albeit not the most efficient one. However, this will only inflate the standard deviation, yet the Table shows that the coefficient estimate on water availability has very limited variation. The coefficient on water rights is very robust to the inclusion/exclusion of a wide array of variables, and stays remarkably robust for all 4096 models. This gives us some confidence that water rights are not correlated with omitted soil variables.[24] However, excluding some of the soil and other variables has strong effects on the optimal number of degree days! This should not be surprising as temperature and hence degree days increases when one moves southward, and the relevant soils in the south (especially Imperial Valley) are rather bad. Degree days therefore pick up some of the variation in soil variables. However, as we have stressed before, in a similar study that relies on a much wider geographic and hence climatic range, we find that the degree days variable peaks around 1800 degree days and the results are again very robust.

A-4. Endogeneity Test

One additional concern with water rights is that they might have been endogenously chosen. For example, one might argue that farmers initially picked the land with the best soil quality and hence the surface water variable is correlated with the site-specific error of a farm. This would upward bias our coefficient estimate on federal and private surface water availability. However, this appears unlikely for two reasons. First, the coefficient on surface water is rather insensitive to the inclusion/exclusion of soil variables even though the soil variables as a group are highly significant. If water rights were correlated with site-specific characteristics one would expect the coefficient estimate to bounce around much more when site-specific soil variables are included/excluded. Second, we conducted a Durbin-Wu-Hausman test to check more formally whether surface water rights are endogenous. An alternative hypothesis would be that surface water rights close to natural rivers are larger as plots close to a river were the only farmable areas when farmers first settled in California. We therefore use the distance to the nearest river as an instrument for water rights. There is considerable variation in our data set ranging from 0.01 to 31km. When we include the error term from the auxiliary regressing where surface water rights of each district are regressed on the distance to the nearest river in the hedonic equation, the t-value on the error term is low at 0.36 and we cannot reject the hypothesis that surface water deliveries are exogenous. Due to the stability of our estimate to different modeling assumptions and the failed endogeneity test we believe that it is unlikely that our coefficient estimate on water availability is biased.

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[24] If a soil variable of great importance had been omitted, one would expect it to be somewhat correlated with the other soil variables, rendering our results sensitive to the inclusion or exclusion of soil variables.