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by

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Abstract

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Coastal agricultural regions are often faced with a series of complex economic and environmental problems. Although coastal microclimates make the production of delicate produce highly desirable, many are at risk of sea-level rise, coastal flooding, and groundwater overdraft. These phenomena lead to seawater intrusion, which contaminates groundwater and reduces agricultural productivity. In this work, I examine the damages from seawater intrusion, as well as a municipal treated wastewater program designed to mitigate its effects.

In the first chapter, I introduce the Pajaro Valley, the setting for the economic analysis of seawater intrusion and municipal recycled wastewater in chapters two and three. The Pajaro Valley provides an excellent study region because of its long-term seawater intrusion issues, the water management agency's high quality monitoring efforts, and the wide variety of specialty crops produced. Within this introduction, I explain the mechanics behind seawater intrusion and its impacts to crop production. I detail the history of intrusion within the Pajaro Valley, as well as the local groundwater management structure and their efforts in staving off further damage. I also introduce the municipal treated wastewater program, other alternate water sources, and the pricing structure for water in the valley. In total, this provides important historical context for the remaining analysis.

In the second chapter, co-authored with Ellen Bruno and W. Michael Hanemann, I examine agricultural producers' willingness-to-pay to avoid saline groundwater. This chapter combines panel measurements of groundwater salinity and high resolution land use data from California's central coast to predict the likelihood that farmers shift crops in response to a change in groundwater salinity. We use observed choices to estimate the impact of salinity on crop choice with a panel mixed logit model, controlling for regional trends and relevant field-level characteristics. Then, we derive measures of the marginal willingness to pay and simulate crop changes under salinity conditions likely to occur with climate change. Our

model indicates that growers are willing to pay between $1,612 and $16,369 per acre for a 10 mg/L reduction in total dissolved solids depending on the crop. Results inform our understanding of the cost of sea-level rise to agriculture.

In the third chapter, I examine the effect of a proposed seawater intrusion mitigation strategy: the development of a municipal treated wastewater program. This paper is the first to empirically evaluate the benefits of recycled water in agriculture. I measure the direct effects of recycled water deliveries, evaluating crop choices and welfare gains for growers receiving water, using a panel mixed logit model. I then measure the indirect impacts, using event studies to measure how recycled water changes the salinity of the underlying water basin. I evaluate the effects for growers that receive recycled water, as well as those who do not have access to recycled water, but farm in the same region. In a high-value agricultural region, I find that growers receiving recycled water shift towards salt-sensitive, profitable crops, with welfare gains of $16 million dollars annually for 5500 acre-ft in delivered water. Salinity of the underlying aquifer, measured using total dissolved solids, improves near parcels receiving delivered water by up to 570 mg/L, and these changes occur in years where aquifer salinity levels are highest. Overall findings suggest that for delicate, profitable produce, recycled water is a promising strategy in mitigating damages from seawater intrusion and groundwater overdraft.

To James

Meeting you was unquestionably the best part of this beautiful journey.

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Chapter 1

Agricultural Water Use, Seawater Intrusion, and Basin Management in the Pajaro Valley

1.1 Introduction

The Pajaro Valley is a productive agricultural region located on the Central California coastline, spanning across portions of Monterey and Santa Cruz counties. It provides an excellent study region for examining the implications of seawater intrusion on agriculture. Seawater intrusion in the region is well-documented, severe, and increasing over time. The local water management agency has done a rigorous job in tracking changes in salinity and agricultural production, as well as monitoring groundwater use. In addition, the region has engaged in large-scale mitigation strategy efforts, with the use of municipal treated wastewater. While the Pajaro Valley has experienced more severe seawater intrusion issues than most coastal agricultural regions, it is also an early adopter of recycled water as an alternative water source. Understanding the dynamics of seawater intrusion and management in this region can provide important implications for other regions wrestling with salinity problems under climate change.

In the Pajaro Valley, approximately 30% of the land and 85% of total water consumption is used for agricultural production. Due to the temperate Mediterranean micro-climate, Pajaro Valley has some of highest valued land in the country. In 2019, the crop revenue generated by the Pajaro Valley was approximately $1 billion across 28,500 irrigated acres (Meusel and Lockwood 2021). The region is well known for a variety of produce, including strawberries, raspberries and blackberries (caneberries), apples, artichokes, and vegetable and nursery products. The major companies Driscoll's (berries) and Martinelli's (cider) are headquartered in the valley. Many of the crops in the Pajaro Valley require a significant amount of water for production, with most requiring between 2-3 acre ft. With virtually no access to surface water (less than one percent of water use), irrigation water is sourced primarily from groundwater sources.

Residential land use (both urban and rural) has increased from 5% of the land area in 1966 to 17% of the area in 2006, as shown in Figure 1.1, from (PVWMA 2014). Agricultural land has increased over the same time frame, but has stayed approximately stable since 1989. The area with native vegetation has decreased. The population is also increasing, leading to additional pressures on water in the basin. However, urban groundwater use has remained relatively constant thus far, due to conservation programs. The City of Watsonville, which is home to more than half of the 80,000 residents living in the Pajaro Valley, is planning to keep urban water use the same, by increased conservation programs and surface water use (PVWMA 2014).

1.2 Groundwater Use and Seawater Intrusion

Groundwater is the primary source of water for the entire basin, making up 93% of the water used in 2020. In fact, the Central Coast relies mostly on groundwater for agriculture, although a few farmers receive water through surface sources, the State Water Project (SWP) and the Central Valley Project (CVP). Less than one percent of the Pajaro Valley's water supply came from surface sources in 2020 (PVWMA 2020). .

On average, total annual groundwater use from 2010-2020 typically ranged from about 50,000-55,000 acre-feet per year (AFY), although this increased up to 60,000 AFY during the height of the 2013-2015 drought (Meusel and Lockwood 2021). Groundwater pumping in the Pajaro Valley is nearly twice the sustainable yield of the basin annually, which is defined as the quantity of water that enters the basin, through agricultural runoff and precipitation. By the 1940s, groundwater depletion was significant enough for growers to adopt deep well turbine pumps from the oil industry in order to reach the groundwater (CWRCB 1953). Artesian wells, which were prevalent until this era, started to be artesian only during winter (or not at all). The installation of the tube wells has led to an additional, significant groundwater concern: that of seawater intrusion.

Seawater Intrusion

Seawater intrusion is the process of ocean water entering groundwater tables, contaminating freshwater resources. Many factors contribute to saltwater intrusion, including irrigation wells, excess pumping of groundwater, climate change, and sea-level rise. Mechanically, seawater intrusion works across four major dimensions. In the Pajaro Valley, the primary movement of seawater into freshwater is lateral (Hanson 2003). When a groundwater aquifer falls below sea-level, it creates a landward gradient where the dense seawater moves horizontally into the freshwater. Secondly, major storms and coastal flooding lead to seawater inundating nearby land, resulting in seawater percolating through the soil and leaching into the underlying groundwater. Additionally, seawater can enter coastal groundwater aquifers from below, since groundwater commonly sits directly on top of seawater, with only the relative density difference separating the two water bodies. The use of tubewells in the freshwater aquifer leads to pressure changes, where the resulting "cones of depression" allow seawater to mix upwards into the freshwater aquifer. Finally, sea-level rise intermingles with seawater intrusion in multiple ways: by increasing the frequency and severity of coastal flooding, and by increasing the extent of the seawater "toe", or how far inland the seawater sits below the groundwater aquifer. Altogether, seawater intrusion is a complex, dynamic system that is difficult to combat once in motion.

Seawater intrusion was first noticed in the Pajaro Valley in 1951, with the extent of seawater intrusion increasing seven-fold since its discovery. However, in years of high rainfall, groundwater levels were historically high enough to prevent significant seawater intrusion. Simulations from the Pajaro Valley Hydrologic Model (PVHM) suggest that before the 1984-1992 drought, groundwater levels only dropped below sea level during drought years. Since 1984 however, the groundwater level has been on a largely continuous decline (Wallace and Lockwood 2010). In 2010, the Pajaro Valley Water Management Agency reported that long-term rates of saline intrusion are about 200 ft/year, and intrusion renders 11,000 acre-feet of water unusable annually. One-half of the groundwater table is below sea-level year round, and two-thirds is below sea level after irrigation season in the fall. Even with fluctuations in rainfall, in much of the Pajaro Valley, today the groundwater table remains consistently below sea level (Wallace and Lockwood 2010).

Seawater intrusion is typically measured by the concentration of chloride present in a water body. However, for agricultural purposes, chlorides affect crops and yields in the same ways as other salts that may be present in irrigation water. Total salt content is generally measured using electrical conductivity (EC) and Total Dissolved Solids (TDS). Irrigation water with a salinity value of less than 500 mg/L TDS is the objective for irrigated agriculture. Strawberries, however, are a particularly salt-sensitive crop, with yields beginning to decline at TDS values of 450 mg/L (Grattan 2002). Irrigation water that has high TDS levels can lead to root and foliar absorption, negatively impacting crop yields[1]. The relationship between irrigation water salinity and crop yields is depicted in Figure 3.4. Plants can typically tolerate salinity in irrigation water up until a crop-specific threshold, at which point yields decline linearly. Additionally, irrigation water that is high in sodium can lead to a loss of soil permeability, especially for soils with a lot of clay (Quirk 1986).

While salinity issues especially impact the coast of the Pajaro Valley, TDS levels vary significantly across the region. As discussed above, there are many channels for seawater intrusion, and transport of water between aquifer layers is possible. Groundwater will move from areas of high to low pressure, through naturally occurring gaps, vertically, or through well bores. The Murphy Crossing area, on the eastern side of the Pajaro Valley, contains especially high levels of total dissolved solids (Muir 1972). The highest chloride levels tend to occur in aquifers consisting of Aromas Red Sands and the Purisima geologic formation,

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[1] Sprinkler irrigation is more likely to lead to foliar absorption, as the water comes in direct contact with the leaves of the crop. Drip irrigation is the most common irrigating technique in the Pajaro Valley (especially for berries), so foliar absorption is less likely to be an issue.

with values from fewer than 5 mg/L to 14,600 mg/L. The average total dissolved solids levels across the Pajaro Valley, from 2003-2020, are shown in Figure **??**. Salinity also varies significantly over time, due to changes in precipitation and groundwater use.

There are other pollutants that lead to water quality concerns in the Pajaro Valley, including nitrates and phosphates. However, while nitrates and phosphates are of concern to human and environmental health, they do not have a negative impact on crop yields. The Central Coast Regional Water Quality Control Board has water quality objectives for its irrigation supplies (CCRWQCB 2019). Nitrate contamination is largely due to fertilizer, while the source of salts is primarily saltwater intrusion, although seawater also contains nitrates. Therefore, while these contaminants are essential to keep track of, for agricultural producers, the concerns are negligible.

1.3 Basin Management

While seawater intrusion had been discovered in the Pajaro Valley in the 1950s, broader management did not take place until a California-wide drought in the late 1970s spurred statewide action. In 1977, the Governor's Commission to Review Water Rights in California was created, and their report contained recommendations to improve groundwater management and overdraft. In 1980, the California Department of Water Resources defined 447 groundwater basins, sub-basins, and other water storage types, and highlighted the Pajaro Valley water basin to be one of 11 basins facing severe overdraft (*1980 - Department of Water Resources Bulletin 118-80, Groundwater Basins in California* 2018). Due to this classification, the Pajaro Valley Water Management Agency (PVWMA) was established in 1984 to combat overdraft and salinity problems by bringing several different groups of stakeholders together. There is a seven member board of directors for the PVWMA. Four are elected every four years by the public (one for each major region), and the other three are appointed by Santa Cruz County, Monterey Bay County, and the City of Watsonville, respectively. The appointed individuals must receive a majority of their income through agriculture, and serve two year terms. There are no term limits. The PVWMA can manage groundwater resources, but it is not authorized to deliver potable water.

The PVWMA completed its first basin management plan in 1994. In the early 1990s, the Pajaro Valley Water Management Agency started a water supply system that combines surface water, groundwater, and recycled water to provide water to farms as well as to recharge the aquifer to prevent seawater intrusion. Today, under the Sustainable Groundwater Management Act, PVWMA is tasked with bringing the water basin into "balance" by 2040, where the water entering the aquifer matches the annual quantity removed. Total water use in the Pajaro Valley is approximately 55,000 acre-feet a year (AFY), with 52,000 AFY sourced from groundwater[2]. Estimates from the PVHM suggest that overdraft in the groundwater basin is approximately 12,000 AFY (Meusel and Lockwood 2021). Through a

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[2] Blended recycled water and surface water for the city of Watsonville are the additional sources of water used in the Pajaro Valley.

combination of water conservation and alternative water resources (such as municipal treated wastewater), PVWMA is tasked to ensure that overdraft is reduced to zero.

Sources of Additional Water

The Pajaro Valley Water Management Agency has embarked upon several strategies to fight the depletion of groundwater in the Pajaro Valley. Their primary objective is to reduce seawater intrusion in the valley, and this is partially accomplished by providing alternate water sources for farmers along the coast. There are three primary programs that have been carried out by the PVWMA, including the Watsonville Recycled Water Facility, the Harkins Slough Recharge and Recovery Facility, and the building of the Coastal Distribution System.

The Watsonville Recycled Water Facility delivers recycled (treated municipal waste) water to growers along the coast. The facility began operation in 2009, and has increased the volume of water deliveries from 2700 AFY in 2010 to 5500 AFY in 2020 (Meusel and Lockwood 2021). The recycled water is tertiary treated to meet California's regulations required for the water to be applied to agricultural land. This involves the removal of all solids greater than 10 microns, and the removal of pathogens using UV filters. After the tertiary treatment process, the main differences between recycled water and potable water are the salinity, nitrate, and phosphate levels[3]. Nitrates and phosphates are useful for irrigated agriculture, as they are the main nutrients in fertilizers, and are therefore not removed during the recycling process. Salinity levels are carefully monitored to not exceed 590 mg/L before being delivered to growers. If salinity levels are too high, the recycled water is blended with water from inland wells, in order for it to fall below the threshold. The water storage at the Watsonville Recycled Water Facility has expanded over time, and additional storage tanks have been approved to be built (PVWMA 2020).

The Harkins Slough Recharge and Recovery Facility is another project by the PVWMA, where water is recharged and stored until needed for agricultural use. It has been in existence since 2002, and was the first groundwater recharge project constructed by the Agency. It stores winter surface water flow as well as irrigation water runoff in a 14 acre percolation basin to use for irrigation during the summer (Meusel and Lockwood 2021). While the PVWMA has a permit to pump 2000 AFY from the Harkins Slough, the reality has been closer to 1000 AFY (with an actual delivered amount of approximately 460 AFY), due to a lack of flow through the Slough and the limited capacity in the recharge pond (PVWMA 2020). There are plans in place to improve the Harkins Slough Project, by installing new shallow extraction wells, upgrading the pump system and filters, and establishing a new recharge basin.

The Coastal Distribution System (CDS) is the delivery mechanism for the recycled water and recovered Harkins Slough water to the section of the Pajaro Valley that has the highest levels of salinity from groundwater intrusion, called the "Delivered Water Zone". The CDS

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[3] The Recycled Water Facility also engages in continuous turbidity monitoring. The health and safety monitoring is done by the Monterey County Environmental Health Department monthly, for total coliform, fecal coliform, *e. coli*, and *clostridium perfringens*.

is a pipeline system that primarily serves farms in coastal southern Santa Cruz and northern Monterey counties. The total length of the pipeline was approximately 20 miles long in 2020, and provided water to 5100 acres. There are plans to extend the CDS further, but all expansion plans are within the confines of the Delivered Water Zone (DWZ) (Meusel and Lockwood 2021). The location of the DWZ is depicted in Figure 3.2. There is a policy commitment to not deliver alternative water outside of the zone until groundwater pumping is no longer necessary within the DWZ. This is unlikely to happen in the near term: 2019 was the first year that growers in the DWZ used more alternative water than they pumped.

Additional projects are on the docket for the PVWMA, mostly pertaining to expanding recycled water storage and increasing recharge. There are plans for additional recharge basins on the San Andreas Terrace (using Watsonville Slough water) and near Murphy Crossing (using Pajaro River water). The College Lake Project is another plan, designed to add additional surface water from an existing lake to the CDS (approximately 2400 AFY). In 2016, the Pajaro Valley Board of Directors approved ReNeM, a five year pilot project that develops multiple Managed Aquifer recharge (MAR) projects using stormwater (Meusel and Lockwood 2021). In addition, PVWMA does have rights to 19,900 AFY of Central Valley Project water, a pipeline was never built to the Pajaro Valley, and they currently lease the water rights to other sources. The length of pipeline required is financially unfeasible. In total, the PVWMA's management strategy, combining the CDS, Watsonville Recycled Water Facility, and Harkins Slough, provided 5200 AF in 2020, which is more than ten percent of the annual groundwater used in the region (PVWMA 2020). Targeting this water as a substitute for groundwater in coastal areas, as well as recharging the groundwater can lead to a mitigation of seawater intrusion.

Project Funding

The Pajaro Valley Water Management Agency has the ability to regulate and limit pumping directly, but has opted for pricing policies and the supplemental water projects described above as an alternative to a command and control program. The price of water varies in the Pajaro Valley depending on where the water is sourced (delivered through the CDS or pumped), as well as if the well is metered or unmetered[4], and if the well is located within the delivered water zone (PVWMA 2014). New rate structures have to be approved by residential, commercial, and agricultural water users. In addition, revenues for water pricing must not exceed the proportionate costs of the property-related service attributable to the parcel that is charged.

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[4] Metering is required for an agricultural well if it serves 10 acres of orchard, 4 acres of berries or row crops, 2.5 acres of greenhouse facilities, or produces at least 10 AFY. For unmetered agricultural use, the PVWMA estimates consumption based on crop type and other factors.

Pricing of Water

PVWMA first began charging a management fee in 1994, and the first water pumping charges were assessed in 2002. In 2010, the current tiered pricing structure was established. Water prices since 2016 can be found in Table 3.1 The following table depicts the augmentation charges, broken down by user type, over the previous decade. After accounting for the electricity costs of pumping groundwater, the total price of groundwater is designed to be higher than recycled water for growers located in the DWZ. Growers in the DWZ who are not connected to the pipeline (and therefore do not have access to recycled water) still face the higher groundwater pricing, as it is anticipated that they will eventually receive recycled water.

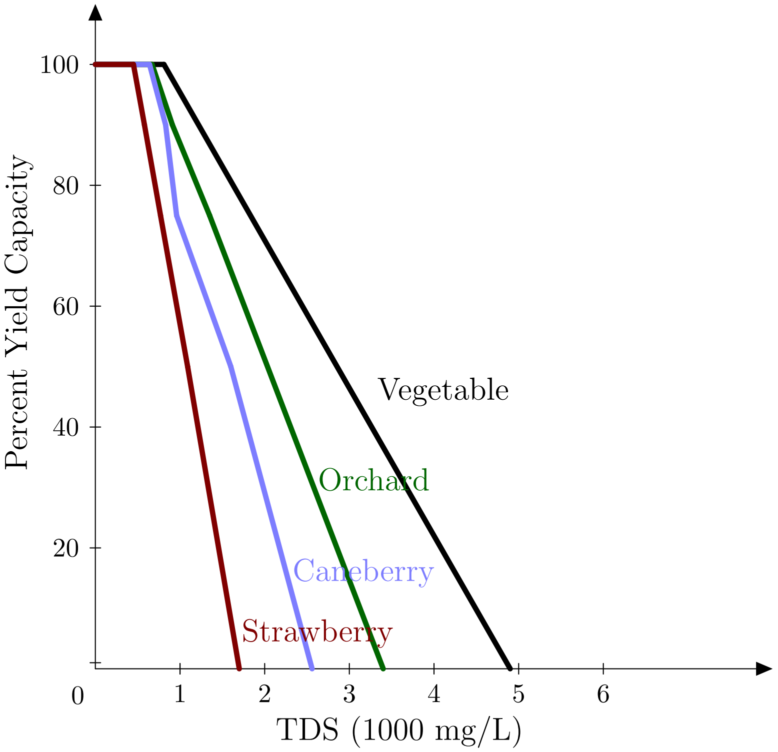
Court Cases and Changes in Legislation

Pajaro Valley Water Management Agency has found themselves in a few legal battles over the water pricing structure. *PVWMA v. Amrhein* was a lawsuit in 2007 that declared that all water prices were property-related, and therefore fell under the rules of Proposition 218. This means that prices charged for water need to be presented at a public hearing, and if a majority of affected owners file written protests at the hearing, the fees are not assessed. In response, the water pricing structure shifted into the tiered pricing structure that is still in use today. *Griffith v. PVWMA* (2013) found that the revenue from water prices could pay for activities associated with implementing the groundwater program, including water conservation. Basically, the court found that the revised water augmentation charges did meet the requirements of Proposition 218, and that the charges benefited the entire basin. This led to upholding the revised augmentation charges in 2010.

1.4 Conclusion

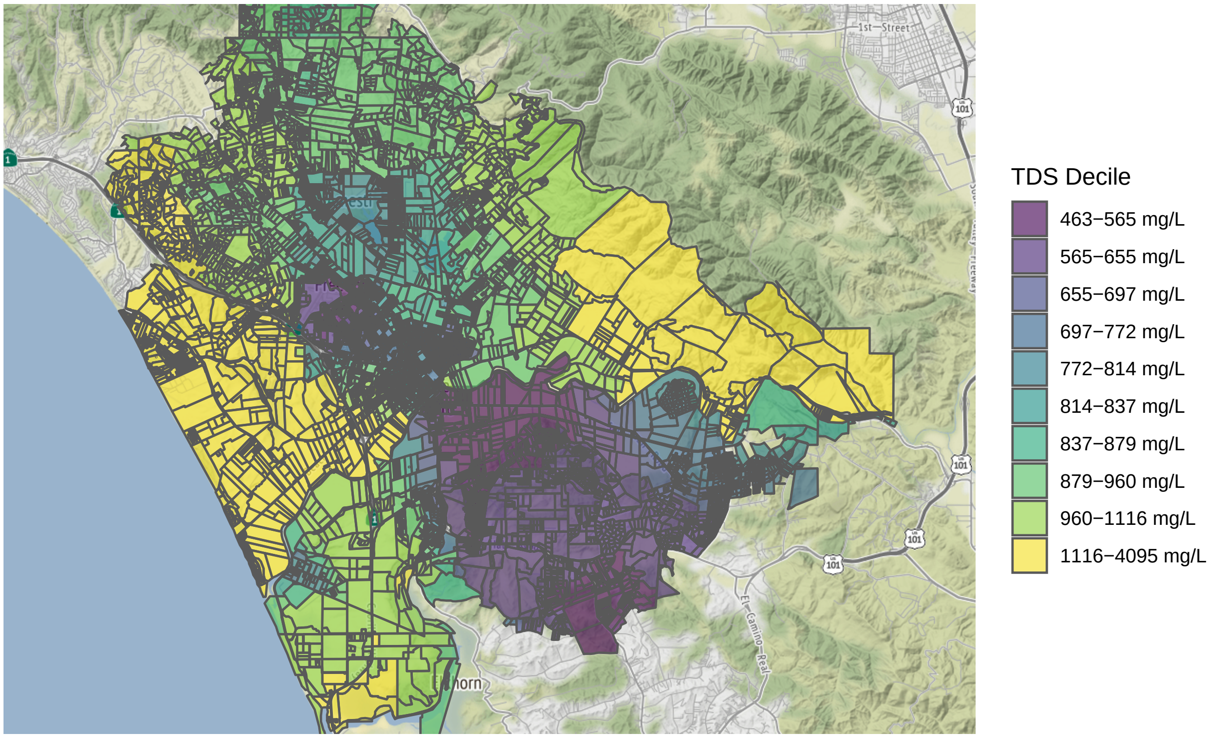
The Pajaro Valley is a unique landscape in which high-value, sensitive agricultural produce meets an ideal but heavily challenged environment. Local government, water managers, and agricultural producers are all committed to keeping the region in agriculture: land is zoned to discourage other types of production, local growers are involved in water projects, and large agricultural firms have located their headquarters in the area. However, the extent of seawater intrusion in the region and the threat of climate change means that there continually be tricky groundwater management issues to face. The use of municipal treated wastewater, conservation practices, and recharge basins is paramount, but salinity damage may be already impacting crop choices and production values.

Figure 1.1: Decline in Crop Yields Due to Salinity



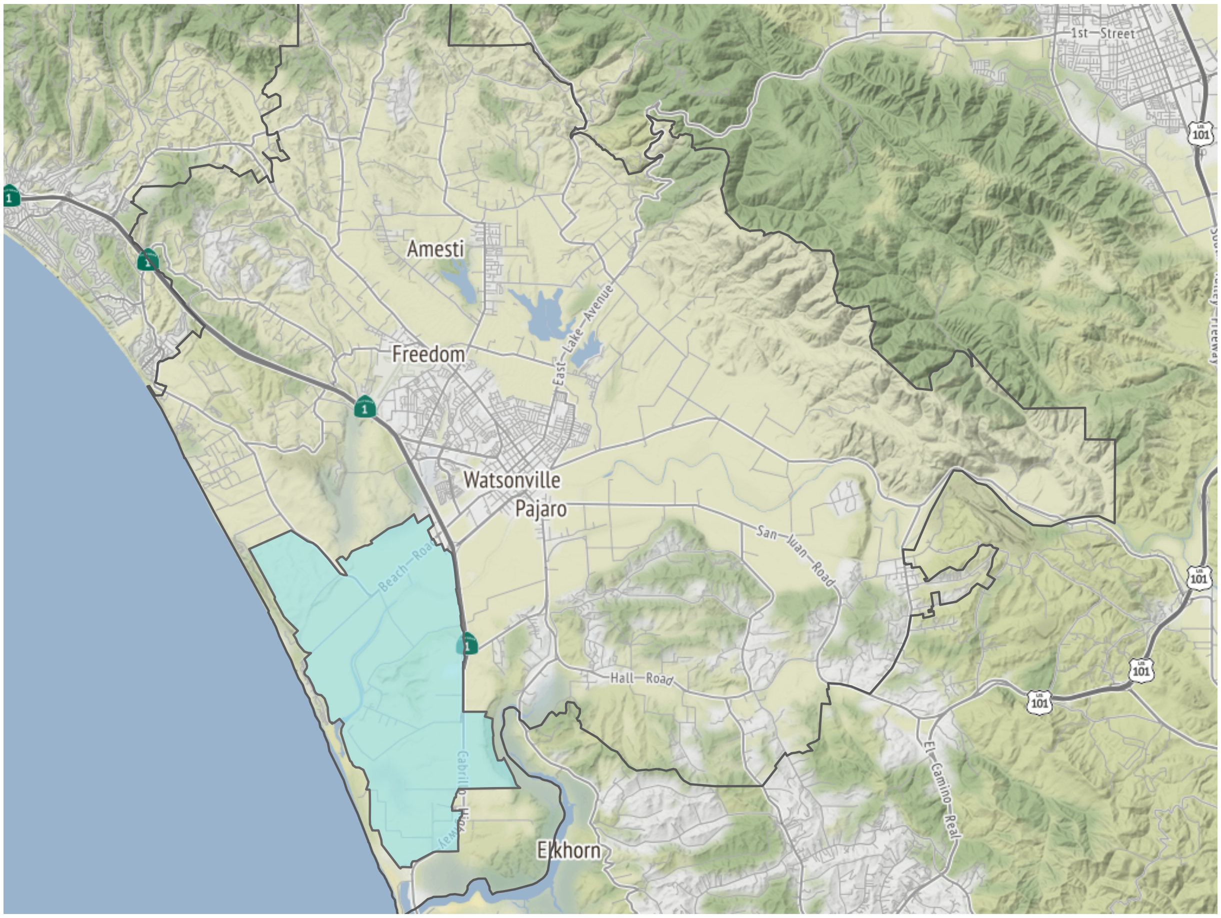
Source: Sears, Bruno, and Hanemann 2022.
Note: The figure depicts the relationship between irrigation water salinity and the maximum achievable yield for major crop categories grown in the Pajaro Valley. Curves are linearly extrapolated from experimental results reported in Grattan 2002.

Figure 1.2: Spatial Variation in Total Dissolved Solids (TDS)



Source: Sears 2022
Note: The figure maps the average TDS (mg/L) from 2003-2020 for all parcels in the water agency service area. Values are interpolated from observations at monitoring wells and averaged across time. Each color represents a decile of average TDS.

Figure 1.3: Pajaro Valley's Delivered Water Zone



Source: Sears 2022

Table 1.1: Summary of Land Use

Land Use Type	1966	1975	1982	1989	1997	2012	2019
Total Agricultural Acreage	30,450	33,410	31,520	34,460	34,650	28,380	28,500
Urban Acreage	4,760	6,690	8,020	8,380	12,860	NA	NA
Native Vegetation	61,300	56,410	56,970	53,660	49,000	NA	NA

Source: PVWMA 2014; Values from 1966-1997 are for the hydrologic model area, while acreage for 2012 and 2019 is from the PVWMA service area only.

Table 1.2: Water Prices in Pajaro Valley, Dollars/Acre-ft

Year	Recycled	GW Pumping (in DWZ)	GW Pumping (outside DWZ)	Residential
2016/17	359	258	203	97
2017/18	369	282	217	103
2018/19	381	309	231	109
2019/20	392	338	246	115
2020/21	392	338	246	115

Chapter 2

Strawberry Fields Forever: Evidence on the Willingness-to-Pay for Groundwater Quality in Agriculture

2.1 Introduction

Dependence on groundwater as a freshwater source has increased significantly over time (Wada et al. 2010). It now accounts for over a third of irrigation water withdrawals worldwide and about half of the domestic needs of the world's population (Rodell et al. 2018). Meanwhile, climate change is bringing warmer temperatures, sea-level rise, and more frequent and extreme weather events (Nicholls and Cazenave 2010; Kunkel et al. 2013). The increased variability of precipitation and the reduction in surface water supplies due to warming temperatures puts additional pressure on groundwater resources. Additionally, sea-level rise will flood agricultural lands, as well as degrade water quality through saltwater intrusion into coastal aquifers (Wong et al. 2014). Since both the quality and reliability of water supplies are crucial for agricultural productivity, this poses a threat to global food production.

To date, the focus of the economics literature on groundwater resources has been on issues related to groundwater supply. Groundwater is a classic common-pool resource whereby, in the absence of well-defined property rights, individual pumpers' actions cause direct, external effects to their neighbors. Recent work is advancing our understanding of the magnitude and nature of the stock and pumping cost externalities associated with extraction (Brozović, Sunding, and Zilberman 2010; Pfeiffer and Lin 2012; Edwards 2016; Merrill and Guilfoos 2017; Manning and Suter 2019), and evaluating the potential for and impacts of different mechanisms to overcome this market failure (Smith et al. 2017; Drysdale and Hendricks 2018; Bruno and Sexton 2020; Ayres, Meng, and Plantinga 2021). In addition, overpumping groundwater can also degrade water quality, particularly in coastal agricultural regions, because it moves seawater into freshwater zones as cones of depression are formed in areas around tube wells (Roseta-Palma 2002). Largely absent from this recent and growing body of groundwater work are questions about water quality.

This paper empirically estimates the marginal damages associated with increasing groundwater salinity. Our approach is based on the idea that the willingness of farmers to switch to more salt-tolerant crops reveals how much they value a change in groundwater salinity. Crop yields decline as salinity increases and switching to a more salt-tolerant crop is the primary mechanism to mitigate these costs (Assouline et al. 2015). Thus, our understanding of the marginal damages of sea-level rise and the willingness to pay (WTP) to avoid saltwater intrusion hinges on an unbiased estimate of the effect of changing water quality on crop choice. In this paper, we use a unique panel dataset on micro-level land use and groundwater quality from California's central coast to provide a credible estimate of the likelihood that farmers switch crops in response to changes in groundwater salinity. Controlling for basin-wide trends and relevant parcel-level characteristics, we estimate the impact of changes in salinity on crop choice with a panel mixed logit model. Then, we use our estimates to derive measures of the marginal WTP and simulate crop changes under salinity conditions likely to occur from continued groundwater overdraft and sea-level rise under climate change.

Our empirical setting – the Pajaro Valley, California – provides a rare opportunity to estimate the WTP for changes in groundwater salinity using a revealed preference approach. Best known for its berries and vegetables, this productive agricultural area has experienced decades of seawater intrusion due to its dependence on groundwater for irrigation and its proximity to the coast. As a result, the water agency that services this region has been monitoring groundwater quality with an extensive network of monitoring wells for decades. The density of monitoring wells allows us to spatially interpolate water quality with minimal error, which is important to a research design that relies on these observable changes in quality over time and across space. Second, we are able to use high-quality geospatial land use data collected by the agency to pair water quality measurements with acres planted in a variety of crops that vary in their salt sensitivity.[1] We take advantage of these observations over both space and time to apply panel discrete choice methods to this agricultural context.

Our results show that an increase in groundwater salinity decreases the likelihood that a farmer will grow cash crops, relative to leaving the land idle, and that the impacts are greater among the more salt-sensitive crops. Our model indicates that strawberry and vegetable growers are willing to pay an average of \$1,613 and \$3,084 per acre, respectively, for a 10 mg/L reduction in total dissolved solids. Blackberry and raspberry producers are willing to pay \$16,369 per acre on average. As a result, a simulation of changes in regional crop production due to a doubling in groundwater salinity projects that blackberry and raspberry production will experience the greatest decline in the region as sea-level rise exacerbates existing saltwater intrusion problems. We estimate that a change in salinity of this magnitude would cost \$140 million, roughly 10% of annual agricultural revenues in the region.

Results carry lessons for other agricultural regions, both coastal and inland. Irrigation of

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[1] This digitized, on-the-ground field survey data is particularly valuable in the California context where alternative remote-sensing data products fail to accurately capture the diversity of crops grown, and may introduce non-classical measurement error as a result (Reitsma et al. 2016; Alix-Garcia and Millimet 2020).

arid and semi-arid lands leads to continuously increasing salt levels in the water and soil over time, even in the absence of seawater intrusion. In fact, 20% to 50% of irrigated agriculture worldwide is already negatively impacted by salinity (Pitman and Läuchli 2002; Assouline et al. 2015). In coastal regions, this effect is compounded by seawater intrusion, which is currently estimated to impact 9% of the U.S. coastline (Sawyer, David, and Famiglietti 2016). To date, saltwater intrusion into California's aquifers has been primarily attributed to the over-exploitation of groundwater (Nishikawa et al. 2009). However, with predictions for sea levels to rise by two to fifteen feet by 2100, this issue will pose an even greater challenge to coastal agriculture in California and beyond (Church and White 2006; Nerem et al. 2018; Befus et al. 2020).

Our papers contributes to a scant empirical literature estimating the effect of changing irrigation water quality. While seawater intrusion is known to be a major issue for coastal agriculture, little research has been done to empirically estimate the economic damages from it (Reinelt 2005).[2] Related empirical studies have estimated the value of groundwater quality to irrigated agriculture in inland regions using hedonics (Mukherjee and Schwabe 2014) and demonstrated the importance of accounting for unobserved heterogeneity in crop choice models (Uz, Buck, and Sunding 2021). Our setting allows us to arrive at a revealed preference measure of the willingness-to-pay for changes in groundwater salinity that accounts for unobserved heterogeneity, providing a key parameter for corrective policies related to groundwater overdraft and saltwater intrusion.[3]

Simulating crop choice and economic damages under changing salinity conditions contributes to discussions about climate change and its impact on agriculture. Globally, there are already many documented cases of seawater intrusion affecting coastal agriculture, such as in Korea, Malaysia, Oman, Vietnam, and Cyprus (Lee and Song 2007; Shammas and Jacks 2007; Tuong et al. 2003; Milnes and Renard 2004). Sea-level rise is conjectured to increase through the end of the century and beyond, and conditions may be exacerbated due to the presence of more severe and prolonged droughts (Church and White 2006; Nerem et al. 2018). To date, much of the literature on the economic impacts of climate change to agriculture has focused on the role of temperature and precipitation. Parallel studies look at yield losses in response to temperatures, and include crop switching (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2005; Lobell and Asner 2003; Deschênes and Greenstone 2007; Lobell et al. 2013). A growing economic literature considers the loss to property values of sea-level rise and other implications for coastal residential areas (Michael 2007; Bin et al. 2011; Walsh et al. 2019; Murfin and Spiegel 2020). Much less is known about the economic impacts of sea-level rise to agriculture.

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[2] Previous research has considered the impacts of saline irrigation water in inland regions using structural approaches, including mathematical programming models (Lee and Howitt 1996; Green and Sunding 2000; Schwabe, Kan, and Knapp 2006; Connor et al. 2012), dynamic process-based models of extraction (Roseta-Palma 2002; Knapp and Baerenklau 2006; Reinelt 2020), and computable general equilibrium models (Bosello, Roson, and Tol 2007; Bosello et al. 2012).

[3] Our estimate provides a complement to studies that consider soil salinity, a distinct but related issue in agriculture, that has been shown to negatively impact agricultural revenues (Welle and Mauter 2017).

Finally, this analysis has important policy implications for groundwater in agricultural regions globally. Optimal groundwater regulation depends on the magnitude of the economic damages of overpumping. Many groundwater basins around the world have already been stressed by persistent over-pumping of groundwater (Wada et al. 2010; Famiglietti et al. 2011). In California, groundwater issues are at the forefront of water policy debates, where groundwater accounts for 40% of the state's agricultural water supply on average. California's Sustainable Groundwater Management Act (SGMA) of 2014 requires overdrafted basins throughout California to reach and maintain long-term stable groundwater levels and correct undesirable outcomes associated with pumping over the next 20 years. The legislation includes specific mandates to local groundwater agencies to address seawater intrusion. Quantifying the magnitude of the costs associated with changing water quality is critical to informing optimal groundwater regulation.

2.2 Background

The Pajaro Valley is adjacent to Monterey Bay on California's central coast. It provides an ideal empirical setting in which to study the effects of changing groundwater quality on farmer welfare for several reasons. First, this productive, groundwater-dependent agricultural region has suffered from saltwater intrusion of the underlying aquifer for decades. Groundwater serves as the predominant source of irrigation water - over 95% of total supply - in the region. Additionally, the agency managing the basin has run an extensive monitoring campaign that has generated unique panel data with which we use to evaluate the damages associated with changing groundwater salinity. Importantly, the region is likely representative of other coastal agricultural regions that will suffer from groundwater contamination due to sea-level rise and overpumping in the coming decades.

Seawater Intrusion and Management

Farmers in the Pajaro Valley are almost entirely dependent on groundwater to irrigate and grow their crops. These groundwater withdrawals, combined with the proximity to the coast, have resulted in seawater intrusion of the underlying aquifer. Seawater intrusion has been documented in the Pajaro Valley since 1951, shortly after irrigation tubewells were introduced in the region.

The seawater intrusion of the underlying aquifer is primarily driven by groundwater pumping, which is nearly twice the sustainable yield of the basin annually. This means that in any given year only half of the extracted groundwater is replenished, through rainfall or from water percolating through the soil after being applied to fields. Seawater intrusion occurs when saline water from the ocean enters a freshwater aquifer. Traditionally, seawater sits below freshwater along the coast, given its higher density from the salt. However, lowered water levels from pumping groundwater faster than the rate of recharge can move seawater to freshwater zones. Depending on location, this can happen laterally, upward (from the deep seawater "toe"), or downward (Bond and Bredehoeft 1987). The extent of the intrusion in the Valley has increased seven-fold since the 1950s (Wallace and Lockwood 2010). Seawater intrusion in the region, on average, moves inland approximately 200 ft/year, and renders 11,000 acre-feet of water unusable annually (Wallace and Lockwood 2010).

In 1980, the Pajaro Valley was one of 11 water basins listed as threatened by severe overdraft by the California Department of Water Resources (DWR 1980). This led to the development of the Pajaro Valley Water Management Agency (PV Water) in 1984, which serves a variety of stakeholders, including farmers and the city of Watsonville. The agency has the authority to conduct an array of basin management activities, including conservation programs, monitoring, recycled water production, and to assess fees to fund these programs. Importantly, the water district established a network of 266 monitoring wells throughout their service area that measure groundwater levels and various water quality parameters. Figure 2.1 shows PV Water's service area and the locations of all the wells monitored by agency. Through this extensive network of monitoring wells, PV Water has tracked groundwater salinity over time and across space, providing rich variation and a unique opportunity to empirically estimate the fraction of farmers that switch crops given a change in groundwater quality.

PV Water has undertaken significant efforts to reduce saltwater intrusion and salinity in the basin. Their primary strategies have been to provide coastal groundwater pumpers an alternative water source for irrigation and to artificially recharge the aquifer. These programs have been executed in coordination with the city of Watsonville through the development of a recycled water facility that treats wastewater from the city, a recharge facility, and a distribution system that pipes recycled water to coastal farms. As a means to allocate limited recycled water supplies, the agency created a "Delivered Water Zone" (DWZ) outlined in Figure 3.7. Only users within this zone can access recycled water. To generate revenue to support these programs, the agency collects fees for delivered water and fees for groundwater pumping in the basin. Our empirical strategy accounts for these important factors which may be correlated with both groundwater salinity and crop choice.

Few other mitigation strategies remain for reducing groundwater salinity. Importing or purchasing surface water from other regions of the state is prohibitively expensive since the Pajaro Valley is not connected to the state or federal water delivery infrastructure. Desalination is also a very high-cost alternative (Welle et al. 2017). And since the mission of the local water management agency is to preserve agriculture in the region, policies to reduce groundwater extraction are unattractive.

Agricultural Production

Known for its berry production, the roughly 30,000 irrigated acres in the Valley produce a range of high-valued fruits and vegetables, including lettuces, artichokes, broccoli, strawberries, blackberries, raspberries, and apples. In 2019, the crop value from the Pajaro Valley was approximately $1 billion. Many of these crops are grown predominately in coastal regions because they thrive in the foggy coastal micro climates. At least 20 different crops fall into the category of "vegetable row crops" grown in this region. The profusion of viable crop choices in the Pajaro Valley is an order of magnitude different from other agricultural regions of the county like the midwestern U.S. However, the diversity of crops here is not unlike other regions of the state or other parts of the California coast.

Groundwater salinity and seawater intrusion is a concern for agriculture because it can impact productivity. Crop yields decline as water salinity increases, which decreases welfare for farmers. Figure 3.4 shows the estimated percent of maximum yield achievable at various levels of irrigation water salinity (measured by total dissolved solids) for the four major crop categories in our study region (Maas and Grattan 1999; Grattan 2002).[4] Different crops have varying salinity tolerances. If, under increasingly saline conditions, a farmer continues growing the same crop, then the crop will face some yield loss due to declining quality, all else equal, resulting in reduced revenues. This profit decline can be mitigated by switching to a less salt-sensitive crop.[5] Figure 2.3 illustrates this tradeoff with a stylistic representation of two crop yield relationships expressed as a function of total dissolved solids. There exists a point at which it is more profitable to switch crops in the face of increasing water salinity.

A look at the approximate revenues generated by these crops helps to demonstrate the significance of these yield declines. A typical parcel growing organic strawberries in this region yields roughly 4,250 trays/acre, which at $13.50/tray would generate $57,375 in revenues per acre. Romaine lettuce fields can produce roughly 750 cartons/acre and at $15/carton would lead to per acre revenues of $11,250.[6] Dropping from 100% to 90% yield capacity would equate to revenue losses of approximately $5,738 and $1,125 per acre for strawberries and romaine lettuce, respectively. Given large potential revenue losses from declines in yield capacity combined with the absence of alternative mitigation strategies, crop switching due to changes in groundwater salinity is likely and the potential damages could be significant.

2.3 Data and Descriptive Statistics

The primary data for this analysis consist of seasonal well-level groundwater salinity measurements and annual, spatial land use data compiled by the water district. These data are supplemented by additional district data on groundwater depth, water prices, and quantities of recycled water delivered to a small subset of farmers. In addition, we collected

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[4] These publications synthesize the many field experiments that have tested the salt tolerance of various crops, generating a picture of the relationship between salinity and yield potential across crops. We constructed a curve for vegetables that reflects the primary vegetable row crops grown in the Pajaro Valley by taking an acreage-weighted average of crop sensitivities using Santa Cruz and Monterey counties' Agricultural Commissioner Crop Reports for 2016.

[5] Adjusting the amount of water applied to the crop through what is referred to as the "leaching fraction" is an additional mechanism that farmers can deploy and is primarily used as a means to adapt to changes in soil salinity. Applying additional water can help flush salts through the soil and out of the root zone, which mitigates the effect of salts on crop growth. However, when the water used to leach salts from the soil is also saline, as is the case for many coastal regions, the effectiveness of this approach is greatly reduced.

[6] These estimates come from University of California Cooperative Extension Cost and Return Studies for Santa Cruz/Monterey/San Benito Counties for 2019. Available here: https://coststudies.ucdavis.edu.

publicly available data on property boundaries, crop prices, and weather. Table 3.2 provides descriptive statistics.

Data on water quality spanning 1957 to 2020 have been collected and provided to us by PV Water. While PV Water reports salinity with a variety of metrics, including electrical conductivity, chloride, and total dissolved solids (TDS), we focus on TDS.[7] TDS is the most common salinity measure used and discussed in scientific articles and outreach publications intended for growers. Second, as opposed to chloride, which strictly measures the salinity from seawater, TDS reflects a broader measure of salt content and is likely more reflective of how growers make decisions. For each quarter, we take all water quality measurements of TDS and use an inverse distance weighting technique to interpolate a map of water quality for the entire Pajaro Valley. On average, there are 68.3 quality measurements in each quarter of our sample period (2009-2020).[8]

Figure 3.6 shows the history of seasonal average TDS values spanning 2009-2020, highlighting strong seasonal salinity patterns in the basin. Throughout the sample period, seasonal TDS levels have averaged 763 mg/L and ranged from a low of 272 mg/L to a high of 17,104 mg/L. Groundwater pumping, drought, and rainfall are known to be the primary drivers of the inter- and intra-annual variation in groundwater salinity that we observe in our setting. In general, salinity reaches its peak at the end of the growing season, which is when groundwater drawdown is at its highest, and before the rainy season begins to recharge the aquifer. Salinity is traditionally at its lowest just before the growing season. In what follows, we focus on TDS observed in the spring season, March through May, since this is the period just before the primary summer growing season. Figure 2.5 provides a sense of the spread in spring salinity observations in and across years, showing that the bulk of observations in this quarter range from 400-600 mg/L and vary from year to year.

Soil characteristics, land elevation, and proximity to the coast are the primary reasons for spatial differences in groundwater salinity across the basin. Figure 3.7 demonstrates this cross-sectional variation by mapping the average TDS of each parcel from 2009-2017. We see that inland regions tend to feature lower average TDS and the parcels within the DWZ seem to have lower salinity than coastal parcels without access to recycled water.

Data on land use were compiled annually for the 2009 and the 2011-2020 growing seasons by PV Water using visual inspection. The district did not collect land use information in 2010. To collect these data, PV Water staff drove from parcel-to-parcel and surveyed the land for crop type and acreage. The survey work involved several quality checks. Hydrology staff evaluated if any areas of land were missed by the initial inspectors, and then digitized the survey. Then, a randomly selected group of 100 parcels were chosen to do a final quality control check to verify that spatial coverage and crop type were correct.

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[7] Nitrates (NO_3) and nitrites (NO_2) are other important pollutants that PV Water collects data on. Their importance stems from the danger posed in drinking water. To our knowledge, these contaminants are not a concern for agricultural users.

[8] Generally, more samples were taken in the second quarter of any given year. By focusing on measurements from just one quarter of the year we avoid sampling issues associated with different number of measurements taken in different quarters over time.

Agricultural land use types include fallow ground, vegetable row crops, strawberries, blackberries and raspberries, blueberries, vine crops, artichokes, orchards, nursery, and unknown agricultural use.[9] Given the limited number of fields that were classified as blueberries, vine crops, and artichokes, we combined vine crops with blueberries, blackberries, and raspberries into one category (labeled caneberries), and combined artichokes in with the rest of the vegetable row crops. Our sample consists of the 726 parcels that remain in agriculture for the full time period with which we observe.

We couple this detailed land survey data with tax assessor ownership and parcel boundary data from the County Assessor offices to form appropriate decision units. These data delineate property boundaries and enable us to assign land use and groundwater quality to each farm at the land parcel level, designated by the Assessor's Parcel Number (APN) in the tax assessor data. The average size of a parcel is 31.94 acres.

Figure 2.7 shows shares of agricultural acreage in the Pajaro Valley classified as one of the primary six crop categories over time.[10] The majority of the acreage in the region is in strawberry and vegetable production. Trends show decreases in strawberry over time, and increases in vegetable production. Both nursery and orchard crops (apples) have held fairly steady during this time period.

Finally, we collected data on other relevant observables that may affect both groundwater salinity and land use decisions–namely, environmental conditions and crop prices. Data on weather (temperature and precipitation) are sourced from PRISM Climate Data, whose roughly 800 meter gridded data are the official climate data of the U.S. Department of Agriculture, and considers elevation, location, and coastal proximity, among other factors in the development of the climate model. We use the gridded monthly mean temperature and cumulative precipitation data in our analysis. We take the centroid of each land parcel in our dataset, and use the weather data for the grid cell corresponding to that centroid. Crop price and average per acre yield data were collected from the annual County Agricultural Commissioner reports which enabled us to estimate a price per acre across each crop category.

2.4 Modeling Framework

Spatially and time-varying groundwater quality and land use data at the parcel level allow us to estimate a discrete choice crop switching model to understand the impact of salinity on farmer welfare. Our research design relies on observable changes in groundwater quality and allows us to control for a suite of observable and unobservable factors that may be correlated with both salinity, crop prices, and crop choice. In what follows, we present our modeling framework and empirical specification, address potential challenges to identification, and discuss the interpretation of the parameters.

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[9] Non-agricultural parcels in our dataset are labeled as residential, industrial, natural habitat, greenhouses, cover crops, and other.

[10] A parcel was designated as growing a certain crop if the majority of acres on that parcel grew that crop. We consider a balanced panel of parcels that remain in agriculture throughout the sample period.

Crop Choice and WTP

We assume each farmer i chooses a crop type j in year t to maximize profits on a given parcel of land, and that each parcel produces a single crop. Profits for growing crop j depend on the output price, p_{jt}. Crop yields, denoted by Y_{ijt} for $j = 1, .., K$ crop types, are a function of groundwater quality and other factors, i.e., $Y_{ijt} = f_j(s_{it}, Z_{it})$ where s_{it} represents salinity of the water for parcel i at time t, and Z_{it} is a vector of other inputs to production. Production functions are assumed to be differentiable and exhibit diminishing marginal productivity to variable inputs. Importantly, we assume $\frac{\partial f_j}{\partial s_i} < 0$ for all $j = 0, .., K$ and $\frac{\partial f_j}{\partial s_i} \neq \frac{\partial f_k}{\partial s_i}$.

We assume farmers will choose the crop that yields the greatest profit. The choice problem is thus:

$$\Pi_{it} = \max_j \Big\{ \Pi_1^*(s_{it}, Z_{it}, p_{jt}), \ldots, \Pi_j^*(s_{it}, Z_{it}, p_{jt}), \ldots, \Pi_K^*(s_{it}, Z_{it}, p_{jt}) \Big\}. \tag{2.1}$$

The crop that yields the highest per-acre profit for given levels of s_{it}, p_{it}, and Z_{it} is optimal. Fallowing, the outside option ($j = 0$), is represented as a special case where the profit margin is zero. We evaluate the profitability of all other options relative to this normalized outside option. The probability that a farmer chooses crop j in year t among K alternatives on a given acre of land, denoted ρ_{ijt}, is:

$$\rho_{ijt} = Prob[\Pi_j^*(s_{it}, Z_{it}, p_{jt}) > \Pi_k^*(s_{it}, Z_{it}, p_{jt})], \forall j \neq k. \tag{2.2}$$

Farmer profits consist of an observable and an unobservable component:

$$\Pi_{ijt} = \pi_{ijt} + \epsilon_{ijt}, \tag{2.3}$$

where the observable portion, π_{ijt}, can be split up by attributes of the crop choices denoted with subscripts j (D_{jt} and p_{jt}), attributes of the individual parcels denoted with subscripts i (Z_{it} and s_{it}), and a time trend t:

$$\pi_{ijt} = \theta_j s_{it} + Z_{it}'\gamma + \alpha p_{jt} + D_{jt}'\beta_i + \delta t. \tag{2.4}$$

Our main parameter of interest, θ_j, reveals crop-specific impacts of changes in groundwater salinity, s_{it}, where salinity is measured by TDS in the spring season prior to planting.[11] γ is a vector of coefficients that captures the effects of factors to production and other parcel-specific characteristics. Included in Z_{it} are both time-invariant parcel characteristics such as parcel size, distance to the coast, and an indicator for the county in which the parcel resides, and time-varying, parcel-level factors such as temperature and precipitation, depth to the

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[11] We assume farmers make planting decisions based on TDS levels of the time period preceding the primary summer growing season, which correlates with the spring season, March through May. Since the majority of the year's precipitation falls between December and March, salinity levels are at their lowest during spring, which forms the basis of their trajectory over the remainder of the growing season. It is reasonable to assume that farmers' expectations about growing season salinity are based on salinity in the period just prior to planting.

groundwater table, lagged crop choice and alternative water supplies and water prices. The impact of crop (output) prices are described by α and assumed to be valued in the same way across parcels. D_{jt} is an indicator for the crop grown. In our mixed logit model, its coefficient, β_i is allowed to vary randomly and with parcel-level characteristics Z_{it} and s_{it}. The time trend captures linear basin-wide trends over time.

If ϵ_{ijt} is assumed to be distributed i.i.d. extreme value, and the outside option (fallowed ground) corresponds to $j = 0$, then the probability of choosing the jth crop can be written as

$$\rho_{ijt} = \frac{e^{\pi_{ijt}}}{\sum_{j=0}^{K} e^{\pi_{ijt}}} = \frac{e^{\pi_{ijt}}}{1 + \sum_{j=1}^{K} e^{\pi_{ijt}}}, \tag{2.5}$$

where the parameters can be estimated by maximum likelihood.

We deploy a panel mixed logit model to estimate the probability that a farmer grows a particular crop relative to leaving the ground fallow. The dependent variable is categorical and indicates whether or not a farmer grows a particular crop (strawberries, vegetables, caneberries, orchard or nursery crops).[12] This econometric choice allows coefficients to vary with both observed parcel characteristics and unobserved random heterogeneity, which captures unobserved heterogeneity in drivers of crop choice over time and correlation of crop choices across alternatives. As a result, this model avoids invoking the Independence of Irrelevant Alternatives (IIA) assumption that troubles multinomial and conditional logit models (McFadden and Train 2000; Nevo 2000).[13]

This flexible approach is particularly important in a setting with perennial crops and repeated observations over time, and in the presence of farmer heterogeneity in response to salinity (Uz, Buck, and Sunding 2021). By estimating crop-specific random coefficients, we are better able to capture the “stickiness” of certain crop choices over time and heterogeneity in crop suitability across parcels. Contrast this with a multinomial or conditional logit model, which would assume crop choices are uncorrelated from year to year. The drawback of our preferred approach is that it precludes us from including two-way fixed effects since no fixed-effects estimator is available for the mixed logit model.

Using estimates derived from the mixed logit model, we are able to estimate the WTP for a reduction in salinity by crop. We divide the marginal utility of reducing salinity for

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[12] Because we have a multinomial choice problem rather than a binary choice problem, our modeling choices include multinomial logit, conditional logit, and mixed logit. Multinomial logit precludes us from estimating impacts of salinity, and thus WTP, by crop because it does not allow for the inclusion of parcel-specific attributes. While conditional logit is not limited in this way, it requires rigid assumptions on substitution patterns across alternatives.

[13] The distributional assumptions on the coefficients define the differences between conditional logit and mixed logit. A conditional logit choice model would specify that $\beta_i = \beta_0 + \beta_1 X_{it}$ (where, in our case, X_{it} includes both s_{it} and Z_{it}). This allows β_i to vary by parcel-specific characteristics. Our preferred structure is to allow β_i to vary with both observed parcel characteristics as well as unobserved random heterogeneity, such that $\beta_i = \beta_0 + \beta_1 X_{it} + \beta_2 \nu_i$, where ν_i is a normal random variable that captures heterogeneity in crop suitability across parcels. This distributional assumption defines a random coefficients mixed logit specification (or simply, a mixed logit). This model allows for a more general unobserved heterogeneity structure in order to capture varying preferences by the farms in our sample.

each crop type by the absolute value of the parameter estimate on crop price α:

$$WTP_j = \frac{\theta_j}{|\alpha|}. \tag{2.6}$$

Since observed crop prices will reflect yield changes due to changing salinity, this ratio can be interpreted as the change in profitability of crop j with respect to salinity.

Empirical Challenges and Identification

One concern with estimating the likelihood that farmers switch crops in response to a change in salinity is the potentially endogenous nature of salinity, s_i. The diverse array of crops that are profitably grown in this region implies that there are many factors influencing crop choice, spanning agronomic, environmental, policy, and market conditions. While primarily driven by weather and climate, which are out of the control of the individual farmer, changes in groundwater salinity can be influenced by basin-wide groundwater pumping and thus potentially correlated with other unobserved economic factors.

To address this concern, we condition on an array of observable and unobservable parcel-specific and basin-wide factors that may be systematically correlated with both salinity and crop choice. Temporal variation in groundwater salinity is primarily driven by two factors: groundwater elevation, which is driven by aggregate groundwater pumping, and weather, both of which may correlate with crop choice. To account for these, we control for precipitation, temperature, and the groundwater elevation at the parcel level. We also condition on distance to the coastline since this is an important determining factor of soil texture and the spatial distribution of salinity in the Valley, and because coastal microclimates determine how well crops grow in certain areas. Features of the parcel, such as its size and crop history, are also likely to influence planting decisions and could be correlated with salinity, and motivate our inclusion of lagged crop choices. Additionally, management and policy choices on behalf of PV Water or the county, like the delivery of recycled water supplies to parcels inside the DWZ and rates charged to generate revenues to fund the program, also influence groundwater dynamics and farmer behavior. Data on these variables allows us to directly account for these factors. Finally, the inclusion of a linear time trend accounts for basin-wide unobservables that may trend linearly with both salinity and crop choice over time.

Residual variation captures other drivers of spatial and temporal changes in salinity that are plausibly independent from crop choice. This includes variation in the landscape that drives percolation and local proximity to wetlands and streams which carry water and flush saline soils. Groundwater flow patterns change when pumping occurs at different depths depending on the subsurface geology being encountered at any given layer in the aquifer, driving plausibly exogenous changes in salinity.

Since our estimates of the WTP are derived by scaling the effect of changing salinity by the absolute value of the coefficient on per-acre crop revenues, we must also concern ourselves with the identification of price effects.[14] The relevant geographic market for the crops grown in this region appears to be worldwide; for example, the U.S. is both an importer and exporter of strawberries, lettuces, fresh vegetables, blueberries, and apples. In fact, the U.S. produces only about 11% of the world production of strawberries in 2017 based on UN Food and Agriculture Organization (FAO) statistics. Given Pajaro Valley's small share in the world market, producers as individual sellers in our setting are unlikely to exercise influence on world prices, lending support for the assumption that the assignment of crop prices is as good as random.

A related concern stems from our use of crop revenues instead of profits to derive WTP. When choosing a crop, what matters to farmers is the difference in profits across crops, not the difference in prices or revenues. Our approach accounts for this with the inclusion of crop dummies and a time trend which capture consistent cost differences across crop and common changes in costs that trend over time. Changes in cost by crop and time not controlled for by crop indicators and a time trend is unlikely to be correlated with changes in salinity or revenues. However, some downward bias may remain in the estimation of α, due to the measurement error in using revenue rather than profit. [15]

Identification of the WTP hinges on the assumptions that, conditional on this suite of relevant spatial and time-varying parcel-level observables and an annual time trend, unobservable factors are not correlated with both crop choice and salinity levels or crop prices. To provide support for this identifying assumption, we will consider a number of alternative specifications. First, we will show the insensitivity of our results to the inclusion and exclusion of a suite of potentially relevant parcel-specific confounders. Then we will show robustness to the exclusion of parcels in the DWZ, the small subset of farmers that receive limited recycled water deliveries, and to a different measure of salinity.

Interpretation

In addition to the identifying assumption, our approach hinges on several modeling assumptions that are critical for the interpretation of our parameter estimates.

First, by designating fallow or idle land as our outside option, we limit our sample to parcels that remain in agriculture throughout our study period and interpret our estimates as the WTP conditional on the land being used for farming. One concern with this is that farmers may be able to exit the agricultural industry entirely in response to changing salinity, which may lead to the conversion of those parcel to industrial uses, growing suburban developments, or natural open spaces and preserves. Heavy agricultural zoning laws in

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[14] Per-acre revenues are calculated by multiplying crop prices by average yields as reported to the County Commissioner's Office. Yield data will reflect changes due to changing salinity in the region, and in this way, our WTP estimate also capture welfare changes due to changing salinity for farmers that do not switch crops.

[15] A complete accounting of farm profits is infeasible due to lack of data on production costs. UC Cost & Return studies exist for many crops, however, they may feature a different geographic region, remain several years (or decades) out of date, and represent coarse approximations that are a function of yields.

this region prevent this kind of switching from occurring in many places and justifies our assumption to denote fallowed land as the outside option. Additionally, the choice to leave agriculture and convert to a different land use type is an irreversible decision best modeled in a dynamic framework.

Second, our approach assumes that farmers can only mitigate the cost of rising groundwater salinity through the channel of crop choice. In other words, our model assumes that no improvements in groundwater salinity can be made in absence of crop switching. In reality, farmers may be able to adjust behavior in other unobservable ways, and these unobservable strategies likely have non-zero costs. For example, a farmer may be able to leach salts through the soil with alternative sources of water or adjust inputs to production to compensate for yield declines due to changing salinity. These mitigation strategies could affect groundwater salinity levels and the agricultural profits that would have been experienced in the absence of crop switching. Because of the potential existence of other unobservable mitigation strategies, the true short-run marginal WTP is likely higher than what we estimate from observable crop switching. We discuss the role of possible alternative sources of water in Section 5.1.

Finally, farmers likely have imperfect information about groundwater salinity levels on their parcel at any given time. Our approach assumes that farmers know the TDS measured in the groundwater at their parcel prior to the growing season and use this information to make their crop choice decisions. However, it is possible that farmers have less than complete information and that observable crop switching reflects this. If so, our revealed preference estimates would likely underestimate their full-information preferences (Greenstone and Jack 2015). Anecdotal evidence suggests that farmers in the region run groundwater quality tests in their private wells at least once a year, with more sophisticated growers testing multiple times a year. Based on PV Water's experience, combined with state-level annual reporting requirements, we believe that the impact of imperfect information is minimal in our setting relative to others.

2.5 Results

Results from our discrete crop choice models are presented in Table 3.3 where each column represents an alternative specification. We report crop-specific estimates of the effect of changing salinity in rows, where salinity is measured as the total dissolved solids (1000 mg/L) from March-May of the growing season. The coefficients on the crop type indicator variables are treated as random variables and are allowed to vary across parcels. Their coefficients and estimated standard deviations are reported in the table. Coefficients on additional independent variables are suppressed.

We first report results from a simple specification with only county fixed effects in column (1). Columns (2), (3), and (4) gradually introduce time-invariant and time-varying, parcel-level observables. Column (2) includes parcel-specific factors that directly affect salinity, including the depth to the groundwater table, the cumulative precipitation from March-May of the growing year, and the average mean daily temperature from March-May of the growing year. Column (3) further conditions on factors related to the parcel that may affect crop choice, including the parcel size, access to an alternative water source of different quality, distance to the coastline, and last season's crop choice. Our preferred specification in column (4), which has the lowest AIC, adds in additional aggregate controls including the agency's water pumping fee and a linear annual time trend. All reported coefficients are relative to fallow ground, which increases in response to an increase in salinity.

Our results demonstrate that, compared to fallow ground, an increase in groundwater salinity decreases the probability that a farmer will grow a cash crop. We see the largest effects among caneberries, one of the most salt-sensitive crops grown in the region. However, vegetables and strawberries are also negatively impacted. Negative but imprecisely estimated effects are observed for orchard crops.

Comparing estimates from columns (2) and (3) suggests that the inclusion of time-invariant parcel characteristics, such as parcel size and distance to the coast, as well as time-varying lagged crop choice and lagged recycled water deliveries is important.[16] Our empirical approach is deliberate in conditioning on an array of factors that are likely correlated with both crop choice and salinity. The inclusion of the annual time trend and water prices in column (4) provides an opportunity to test if our estimates of WTP are robust to their inclusion. The stability of our estimates between columns (3) and (4) lends credibility to our identifying assumption that, conditional on observables, salinity is uncorrelated with unobservables that may impact crop choice.

A look at the marginal effects reveals how crop shares in the region change due to salinity. Using the estimates from column (4) of Table 3.3, we hold the control variables constant at their average levels and show the predicted share of parcels in each crop type under a constant basin-wide TDS level of 2000 mg/L in Table 2.3. This is depicted relative to the average share of crops by type in the sample period. We see that given this increase in TDS of almost 1,360 mg/L, fallow ground would increase from 10.6% of parcels to 12.3% of parcels, holding all other variables at their averages. Likewise, vegetables and strawberries would increase slightly by 1.3 and 1.7 percentage points, respectively, and caneberries would decline by 4.5 percentage points. An increase in vegetable crops relative to fallowed land due to a change in salinity, holding all else constant, is intuitive due to their insensitivity to salt relative to the other regional crops, as shown in Figure 3.4. Interestingly, shares of strawberries also increase and the greatest declines are observed in caneberries, despite strawberries being relatively more salt sensitive. This may reflect the relative value per-unit of these crops or the fact that strawberries are often times rotated with vegetable crops such as broccoli, lettuce, and cauliflower for pest and soil management.

We next use these estimates to deduce growers' willingness to pay (WTP) for a reduction in groundwater salinity. We focus on crops whose estimates in Table 3.3 were significant at the 95% confidence level or greater, namely, vegetables, strawberries, and caneberries. The

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[16] The sample size changes due to the inclusion of two lagged variables. Results of the specification in column (2) are similar when we drop 2009.

willingness to pay estimates for a reduction in groundwater salinity of 10 mg/L are reported in Table 4. While these willingness-to-pay estimates are wide-ranging, the high dollar values indicate that growers highly value water with low salinity levels. These WTP estimates are on the same order of magnitude as the expected revenue losses from a drop from 100% to 90% yield capacity as shown in Figure 3.4. To put these magnitudes into perspective, row cropland in Monterey and Santa Cruz Counties in 2021 ranged in value from $28,500 to $75,000 per acre, representing some of the most expensive cropland in the state. Contrast this to the range of values observed in 2021 for well-dependent cropland in Fresno county which ranged from $10,000 to $16,000 per acre (California ASFMRA 2021).

Robustness

To assess the robustness of our results, we test the sensitivity of our results to two modeling choices. First, we take a closer look at our measure of salinity, which can be measured in different ways. We chose to focus on TDS in our main estimation, since it is widely used in the agronomic literature and is a measure of general salinity. This allows us to look at results that may be applicable across multiple types of salinity problems (not just seawater intrusion). One concern may be that growers actually respond to an alternative salinity metric when faced specifically with seawater intrusion. Chloride is a measure of salinity that specifically captures seawater intrusion, rather than salinity from other sources, such as soil, rock, or other natural materials. Table 2.5 reports marginal effects based on the estimation of our preferred specification from the last column of Table 3.3, except we replace the salinity variable with chloride measurements. On average, chloride levels are 15% of TDS values, so an increase in chlorides to 300 mg/L is similar to a shift in TDS to 2,000 mg/L. As shown, results are largely the same across these two highly correlated measures of salinity. Larger marginal effects are estimated for vegetable row crops and caneberries when using chlorides, which may be due to the fact that the spatial distribution of chloride concentrations is different than that of TDS.

Finally, we take into account the possibility that other water resources may be available to a subset of growers in the Pajaro Valley. Farmers located near the coast experience some of the highest salinity levels relative to the rest of the basin, and simultaneously impose the greatest externality on others when they pump groundwater. PV Water recognizes this, and in collaboration with the growers in the basin and the City of Watsonville, set up the Delivered Water Zone and a distribution system to deliver recycled water and other alternative supplies to the growers most impacted by seawater intrusion. The distribution system serves roughly 15%, or 5,000 of the 30,000 acres farmed in the Valley. The total quantity delivered has slowly increased from 667 AF in 2005 to 4,203 AF by 2016. This is a small fraction of irrigation water used within the DWZ, but it is likely still relevant for farm-level decisions.

It is plausible that growers inside the DWZ have different projections of their future access to high quality water and are less responsive to groundwater salinity, compared to growers without access to delivered recycled water. In addition, anecdotal evidence from conversations with growers in the Valley suggests that growers inside the DWZ who had been unable to plant strawberries before they started receiving deliveries are now able to plant the salt-sensitive crop once again.

While we conditioned explicitly on recycled water deliveries to farmers inside the DWZ in our initial estimation, we perform a robustness check by removing all parcels within the DWZ, to focus solely on the effects of salinity on crop choice when there are no other water sources available. The fraction of parcels planted in various crop categories differs for this subset so marginal effects in this case need to be compared to a different baseline. Marginal effects from the estimation of salinity impacts on this subsample are shown in Table 2.6. Results are very similar in magnitude and significance to those reported in Table 2.3, suggesting that the existence of the DWZ is not biasing our estimation of the relationship between salinity and crop choice.

Simulation

Finally, we ask the question of what would happen to crop choices and to consumer welfare under a scenario in which the quality of groundwater deteriorates significantly across the basin. We simulate and compute the utility-maximizing crop choices for each parcel in each year under a high TDS scenario and plot the distribution. To do this, we keep the estimated marginal utilities for the attributes of crops, parcels, and climate variables the same as in the panel mixed logit model displayed in column (4) of Table 3.3. For each parcel, we estimate the probability of choosing each crop type and use these to predict each parcel's baseline crop choice. Then, we recalculate the probabilities of each crop being grown for each parcel after altering the vector of TDS values to reflect a higher salinity scenario.

Ideally, we would simulate the change in TDS predicted by a climate change model of sea-level rise. This exercise is challenged by the fact that model predictions of sea-level rise, while necessary, are insufficient for deploying our model of crop choice. To use climate model output in our simulation, we would need to map sea levels to the salinity concentration in the groundwater wells on each parcel throughout the Pajaro Valley. Doing this would require the use of a hydrologic model of the groundwater basin, which is beyond the scope of this paper. Further, seawater intrusion is highly influenced by demand for groundwater resources, so the decomposition of changes in salinity to either sea-level rise or to groundwater overdraft is challenging. Climate change is predicted to cause higher temperatures and more variable precipitation, which may lead to increasing demand for groundwater, in addition to a rise in sea levels (Nicholls and Cazenave 2010; Rahmstorf 2007).

Instead, we opt to model a realistic increase in TDS by looking at how much groundwater salinity has increased in the basin over our sample period. The average spring TDS during our sample period is 644 mg/L. From 1990-2020, four years had an average TDS greater than double this value, with an average increase of 10% annually. For a relatively straightforward simulation, we increase the current-period TDS by 100%, to see how crop choice would evolve with this plausible shift in salinity. All other variables, including weather, remain stable for this analysis, which allows us to focus on how salinity specifically impacts crop choice distributions.

The estimated change in the distribution of crop choices is plotted in Figure 2.8. The graph plots the difference between the original model estimates of crop choice and the simulated estimates of crop choice under an increase in TDS conditions of 100%. Caneberries experience the largest shift in parcels planted under the 100% increase, which coincides with their sensitivity to salinity, as well as their relatively lower profitability when compared to strawberries, another salt-sensitive crop. Vegetables experience the largest increase in the probability of being planted, as they are the least salt-sensitive. Fraction of land left idled also increases substantially under the high TDS scenario.

Finally, we estimate how the distribution of welfare is impacted with this change in salinity. Following the procedure outlined by Small and Rosen (1981), where a change in welfare corresponds to the compensating variation for an increase in salinity, expected welfare is defined as:

$$E[W_i] = \frac{1}{|\alpha|} \ln \sum_j \exp\left(\pi_{ijt}\right) \tag{2.7}$$

We estimate the welfare under the original TDS levels, and then re-estimate welfare with respect to the predicted choices made with the increase in TDS. The kernel densities of welfare under both conditions are reported in Figure 2.9. Across the full distribution of parcels, there is a significant decline in welfare when TDS increases. This is expected, as salinity has no beneficial impact to yields, although the magnitude of the negative impacts do vary across crop types and land characteristics. In total, we estimate that the welfare loss due to a 100% increase in TDS amounts to \$140 million. Constituting roughly 10% of total agricultural revenues from the region in 2019, this represents a large and realistic reduction in economic returns for the region if sea-level rise and overpumping continue to threaten groundwater quality.

2.6 Conclusion

Seawater intrusion, which occurs when saline water from the ocean enters a freshwater aquifer, can manifest from two primary drivers: groundwater extraction and sea-level rise. Pumping groundwater faster than the natural rate of recharge can move seawater to freshwater zones, and sea-level rise alters where saltwater sits relative to freshwater in the aquifer (Ferguson and Gleeson 2012). Salinity is a major concern for coastal agricultural production that is dependent on groundwater for its water supply (Sherif and Singh 1999), but it can also have significant impacts on inland irrigated agriculture as salts accumulate in the soil over time. Increased salinity levels in agricultural water lead to declines in agricultural productivity, and farmers are left with few mitigation strategies.

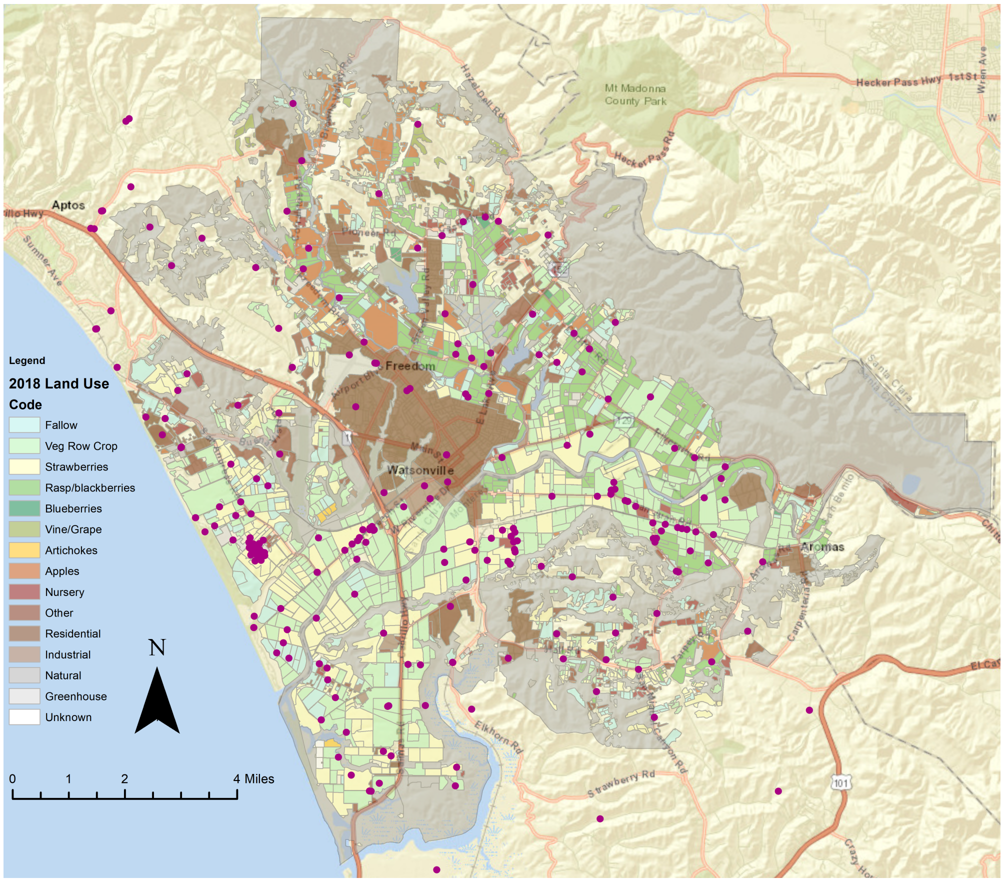
In this paper, we empirically evaluate the likelihood that farmers switch crops in response to changing groundwater salinity, with an application to the Pajaro Valley, a coastal region in California. The willingness of farmers to switch to more salt-tolerant crops speaks to the value of irrigation water quality. Unique spatial panel data on groundwater quality and land use spanning 11 years lends itself to a panel mixed logit model of crop choice. This revealed-preference approach allows us to estimate the marginal willingness-to-pay for improvements in irrigation water salinity.

We find evidence that growers are more likely to shift away from crops that are salt-sensitive, such as strawberries and caneberries, relative to fallow ground, when facing an increase in groundwater salinity. The marginal WTP to pay for a 10 mg/L reduction in TDS varies by crop, and ranges from \$1,613 for strawberry growers to \$16,369 for caneberry growers. Our simulation of a 100% increase in TDS across the basin speaks to potential land use changes in the basin if salinity trends continue. We estimate that a change in TDS of this magnitude, which could realistically occur in a future defined by sea-level rise and continued groundwater overdraft, would result in a welfare reduction of \$140 million.

While our WTP and marginal damages estimates are restricted to an agricultural region defined by the jurisdiction of a single water management agency, most groundwater management decisions and investments are made at this scale. The paucity of robust, geospatial groundwater quality data that can be paired with accurate planting information precludes us from deriving estimates in other regions. While salt sensitivity is crop specific, which will drive differences in the WTP across regions, this methodology is generalizable and can be applied elsewhere to determine the benefits of reducing groundwater salinity.

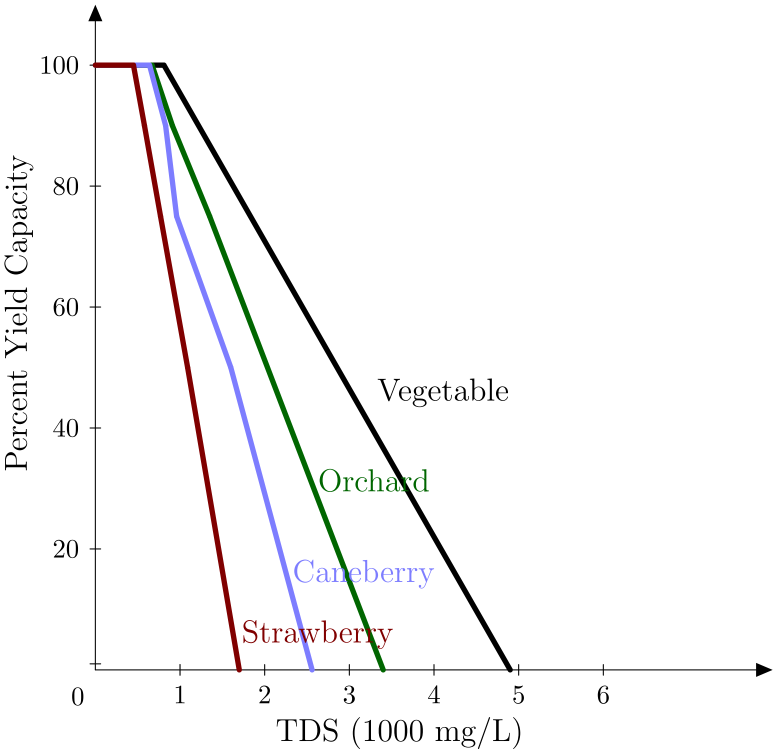
Salinity is becoming an increasingly common issue across the United States and the globe as sea levels rise and groundwater aquifers become more stressed under climate change. Estimating marginal damages from changing salinity can provide new context for the cost of climate change and the cost of groundwater overdraft, both of which are broadly important for groundwater management.

Figure 2.1: Monitoring Wells and Agricultural Fields, Pajaro Valley, CA



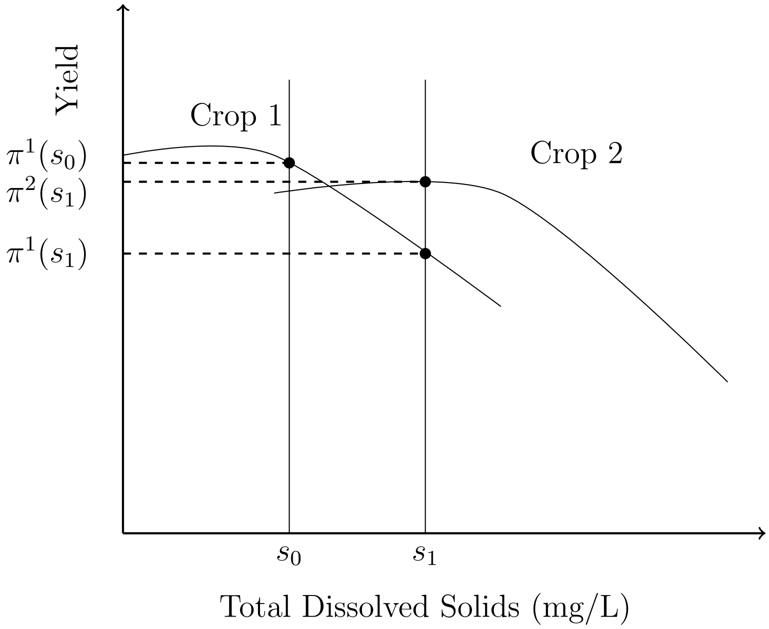
Note: Each point represents a monitoring well operated by PV Water. Monitoring wells overlay land use in 2018.

Figure 2.2: Decline in Crop Yields Due to Salinity



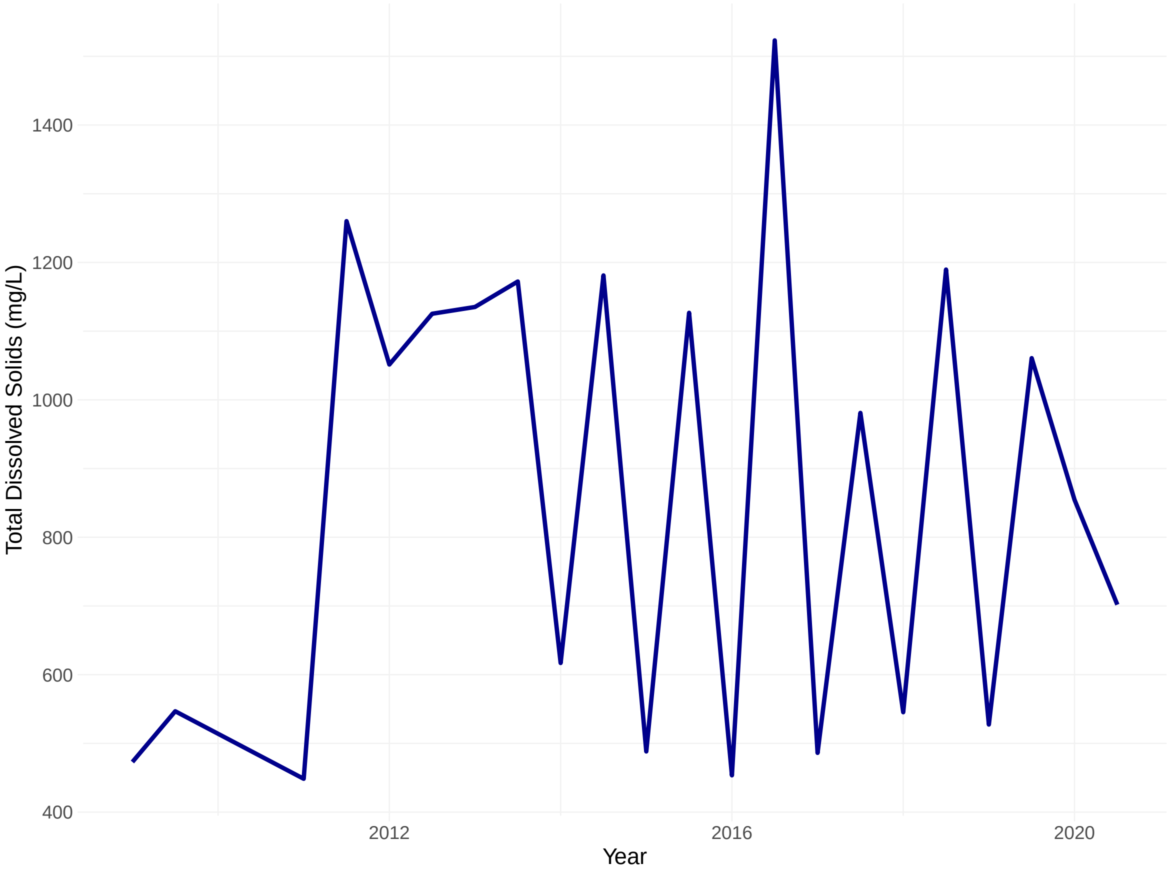
Note: The figure depicts the relationship between water salinity and the percent of maximum yield achievable for the crops grown in the Pajaro Valley. Curves are linearly extrapolated from experimental results reported in Grattan 2002. "Caneberry" includes blackberries, raspberries, blueberries, and vine crops, while "orchard" refers to apples. We constructed a curve for vegetables that reflects the primary vegetable row crops grown in the Pajaro Valley by taking an acreage-weighted average of crop sensitivities using Santa Cruz and Monterey counties' Agricultural Commissioner Crop Reports for 2016.

Figure 2.3: Yields as a function of water salinity



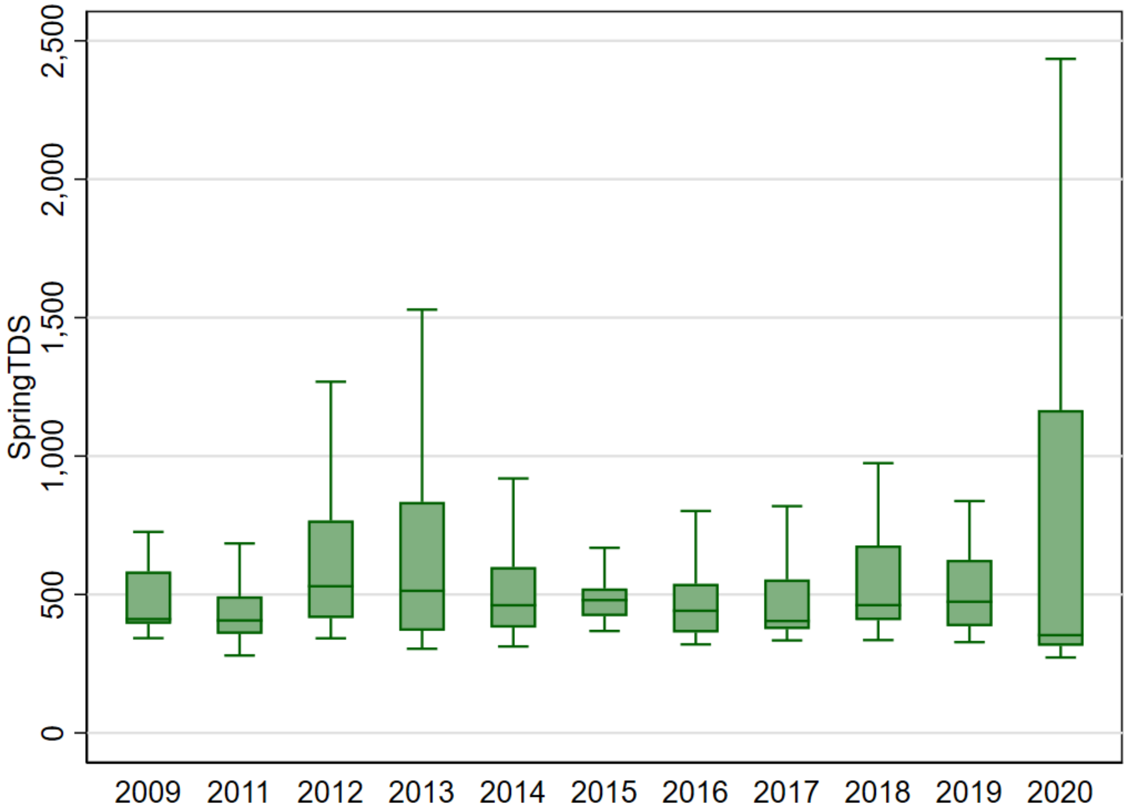
Note: This stylized figure shows yield curves as a function of water salinity when crops vary in salt sensitivity.

Figure 2.4: Average Total Dissolved Solids (TDS) by Season



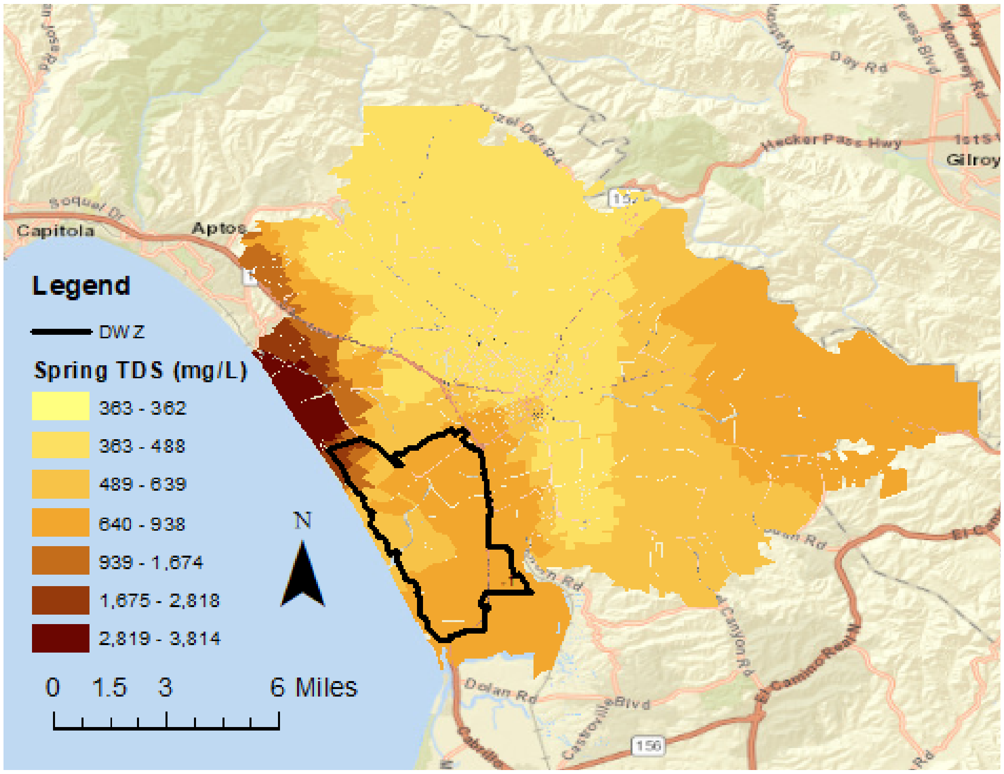
Note: Figure shows fall and spring average TDS (mg/L) in groundwater from 2009 to 2020.

Figure 2.5: Total Dissolved Solids (TDS) in Spring Only



Note: Box plots excludes outside values (values 1.5x larger or smaller than upper or lower quartiles, respectively). Spring is defined as March through May, the quarter preceding the main growing season.

Figure 2.6: Spatial Variation in Total Dissolved Solids (TDS)



Note: The figure maps the average spring TDS (mg/L) from 2009-2020 for all parcels in the water agency service area. Values are interpolated from observations at monitoring wells and averaged across years. The Delivered Water Zone (DWZ) is outlined in black.

Figure 2.7: Shares of Agricultural Acreage by Crop Type over Time, Pajaro Valley (2009-2020)

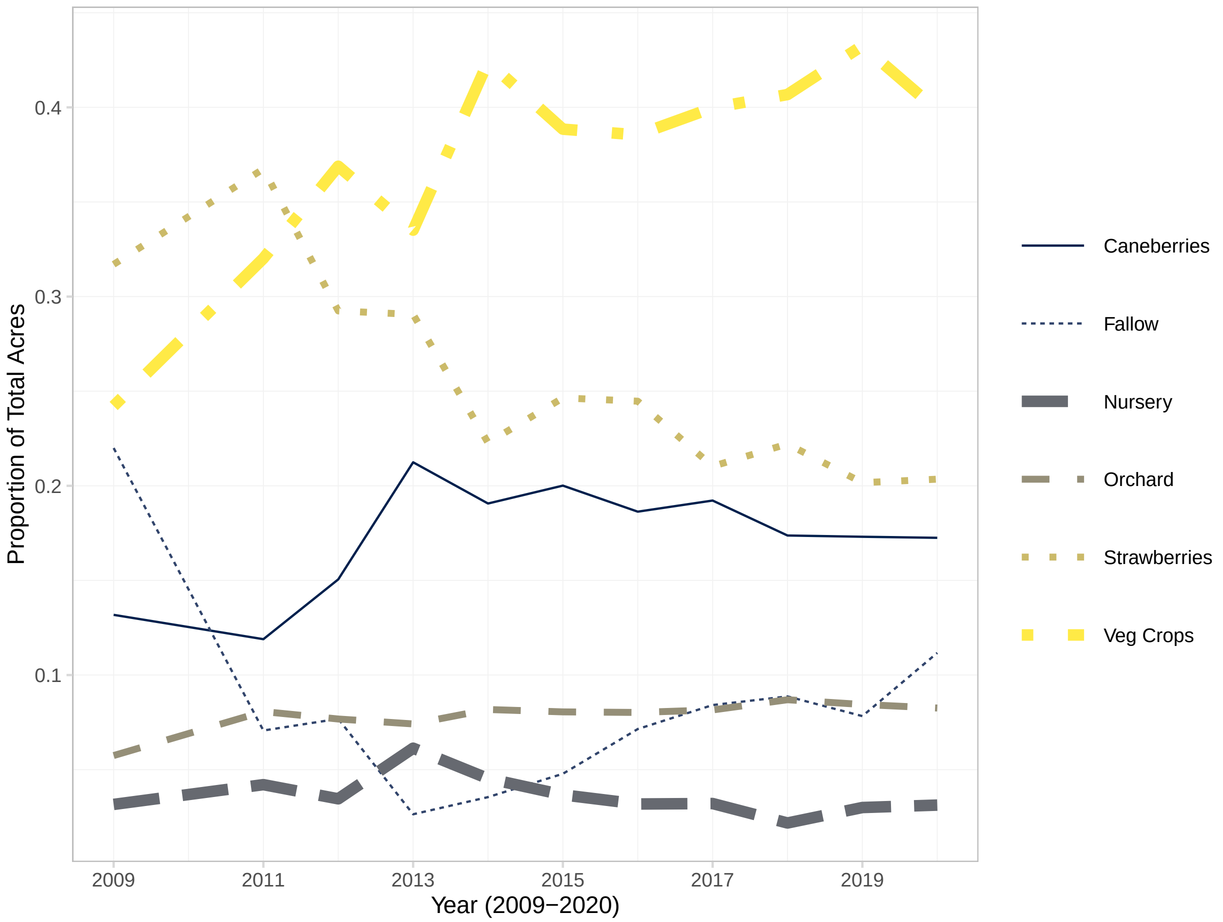
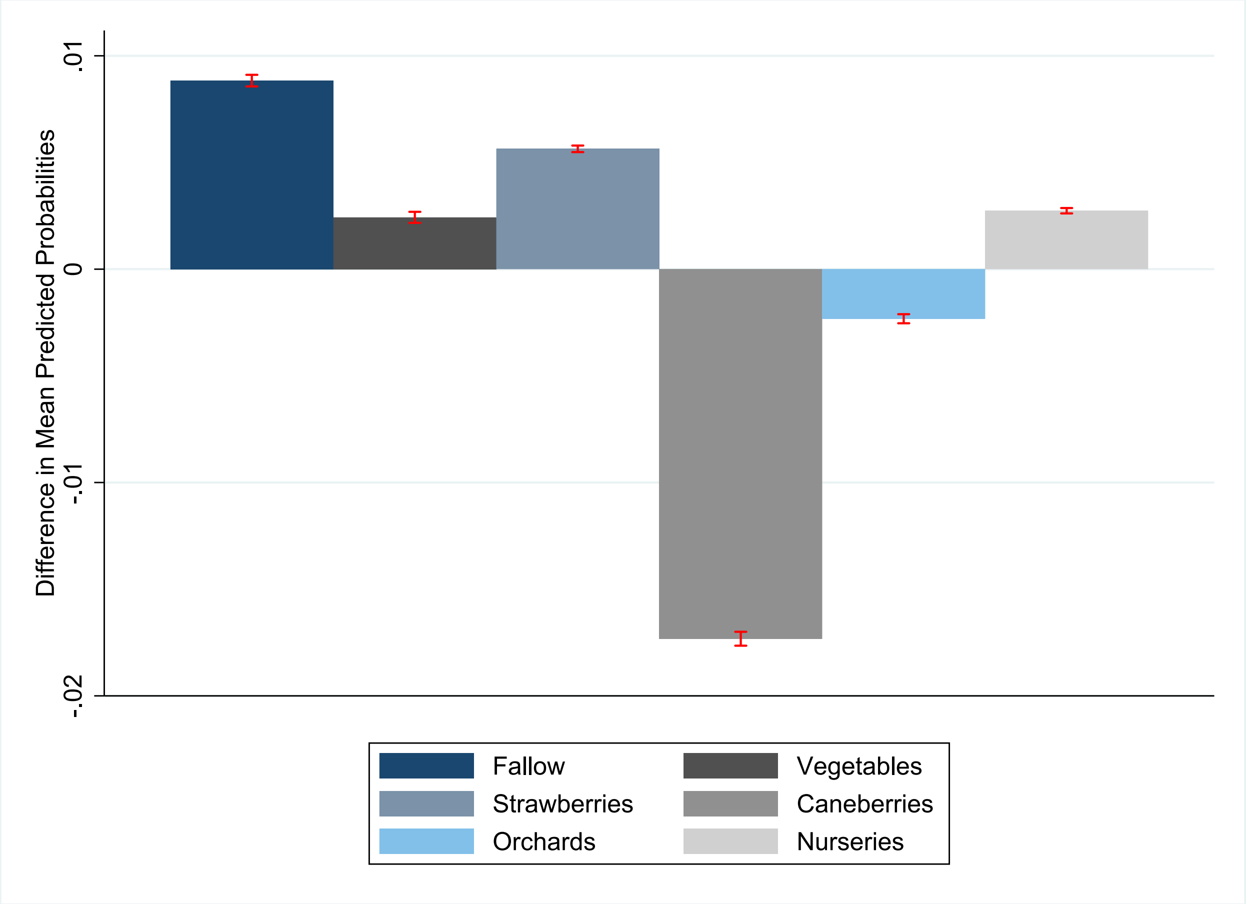


Figure 2.8: Difference in Estimated and Simulated Changes of Crop Choice under Projected Increases in TDS



Note: The figure plots the simulated change in the distribution of crop choices under a 100% increase in TDS.

Figure 2.9: Kernel Density of Welfare: Current TDS and 100% TDS Increase

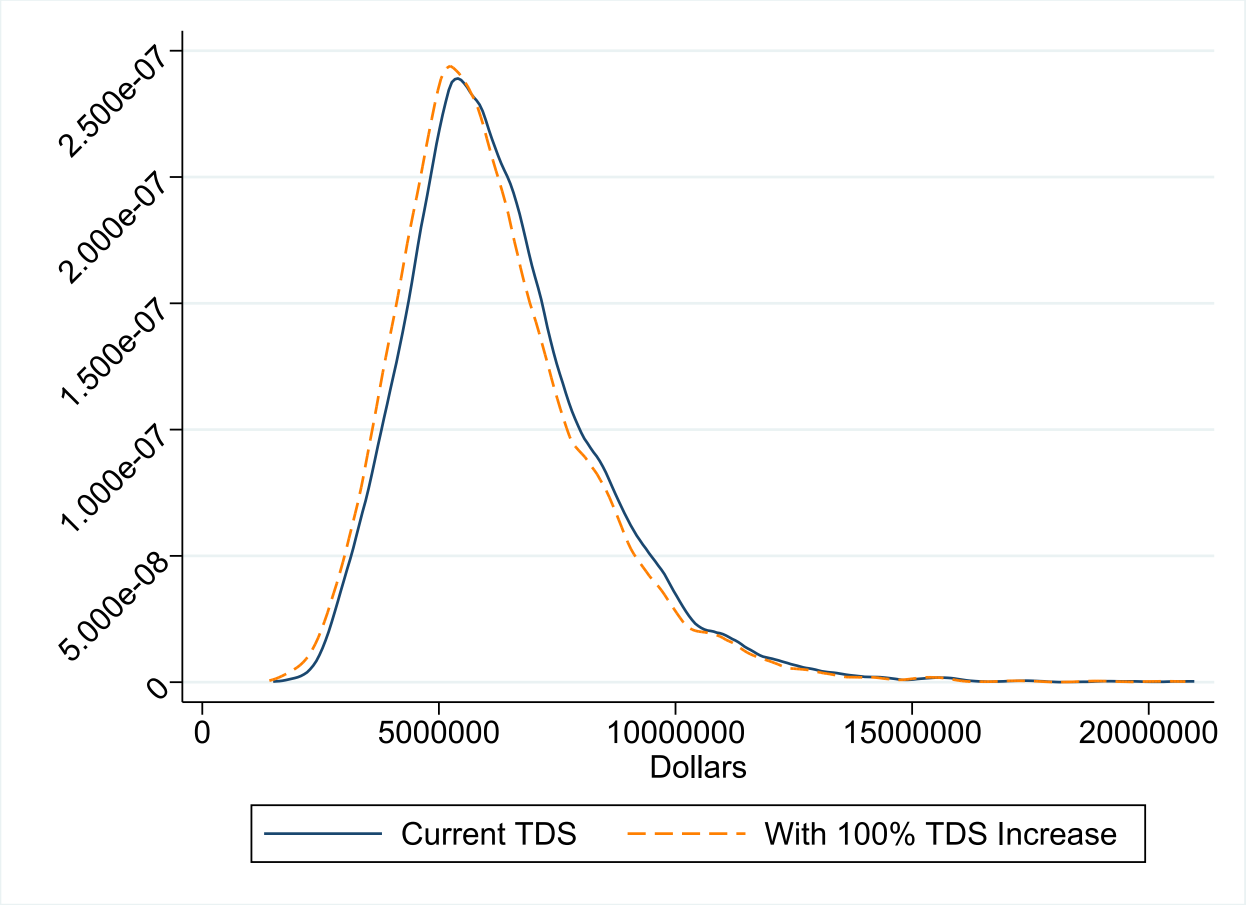


Table 2.1: Descriptive Statistics

	Mean	SD	Min	Max
Environmental Variables (parcel-year)				
Fall TDS (mg/L)	1,078.98	1,396.31	258	12,799
Spring TDS (mg/L)	643.67	999.47	272	17,104
Groundwater Elevation (ft)	-1.91	7.06	-20	40
Distance to Coast (meters)	28,179.13	4,158.65	20,013	37,762
Fall Precipitation (mm)	86.85	55.18	15	286
Spring Precipitation (mm)	152.82	70.53	26	304
Fall Temperature (C)	15.61	0.96	13	18
Spring Temperature (C)	13.32	0.80	11	15
Delivered Water Zone (DWZ)	0.21	0.40	0	1
Lagged Delivered Water (AF)	806.78	1,656.59	0	5,213
Land Use (parcel-year)				
Parcel size (ft^2)	1,389,448	1,700,481	4,922	16,073,640
Fallow	0.11	0.31	0	1
Vegetable Row	0.31	0.46	0	1
Strawberry	0.22	0.41	0	1
Caneberry	0.20	0.40	0	1
Orchard	0.11	0.31	0	1
Nursery	0.05	0.22	0	1
Prices (region- and basin-year)				
Groundwater Assessment Fee ($/AF)	201.04	55.98	80	338
Vegetable Row price ($/acre)	10,722	1,614	8,441	13,113
Strawberry price ($/acre)	67,164	7,697	54,029	78,387
Caneberry price ($/acre)	55,773	6,686	42,492	71,308
Orchard price ($/acre)	206,497	571,273	6,854	1,914,633
Nursery price ($/acre)	223,260	65,653	131,740	358,359

Note: This table reports means and standard deviations for parcel-year, region-year, and basin-year observables. TDS stands for Total Dissolved Solids and is a measure of water salinity. Crop choice is expressed with dummy variables equal to 1 if the majority of that parcel is planted in that crop. Reported TDS measurements are interpolated observations from Spring (March, April, May) and Fall (September, October, November). Precipitation is cumulative and temperature represents the average daily maximum. Groundwater elevation is measured in feet above mean sea level; negative values reflect feet below sea level. AF stands for acre feet. Delivered Water Zone is a dummy variable equal to 1 if the parcel is located inside the zone. Crop prices are county area-weighted averaged lagged one year. "Caneberries" include blackberries, raspberries, and blueberries and "orchards" include apples and vineyards. Distance to the coast is calculated with CA's official boundary.

Table 2.2: Effects of Groundwater Salinity on Crop Choice

	Crop Choice	Crop Choice	Crop Choice	Crop Choice
Average Price$_{t-1}$	2.08e-07**	1.65e-07	2.17e-07	4.04e-07***
	(8.62e-08)	(1.56e-07)	(1.85e-07)	(1.48e-07)
1(Vegetable)	0.309**	1.594	3.880***	5.581***
	(0.123)	(1.143)	(1.344)	(1.534)
1(Strawberry)	-0.014	6.104***	11.735***	12.258***
	(0.117)	(0.987)	(1.220)	(1.396)
1(Caneberry)	-0.032	-6.627***	-9.509***	-9.724***
	(0.207)	(1.749)	(2.787)	(2.995)
1(Orchard)	-4.663***	-12.861***	10.685**	0.153
	(0.670)	(3.684)	(4.148)	(4.852)
1(Nursery)	-4.889***	-9.132***	6.392*	8.362**
	(0.524)	(3.454)	(3.702)	(3.554)
SD Vegetable	1.364	1.216	1.330	1.334
	(0.085)	(0.079)	(0.098)	(0.097)
SD Strawberry	0.998	0.791	0.645	0.683
	(0.087)	(0.078)	(0.113)	(0.112)
SD Caneberry	3.044	2.930	2.759	2.771
	(0.216)	(0.137)	(0.272)	(0.240)
SD Orchard	5.999	6.255	6.165	6.014
	(0.657)	(0.452)	(0.800)	(0.740)
SD Nursery	4.388	4.401	3.927	3.924
	(0.418)	(0.269)	(0.657)	(0.605)
Vegetable TDS	0.018	-0.006	-0.117**	-0.125**
	(0.059)	(0.053)	(0.048)	(0.050)
Strawberry TDS	0.084	0.032	-0.073*	-0.065*
	(0.056)	(0.047)	(0.040)	(0.040)
Caneberry TDS	-0.351**	-0.294**	-0.498*	-0.661**
	(0.137)	(0.125)	(0.272)	(0.298)
Orchard TDS	-0.252	-0.311	-0.396**	-0.371
	(0.247)	(0.196)	(0.198)	(0.231)
Nursery TDS	0.156**	0.130*	0.002	0.001
	(0.076)	(0.068)	(0.053)	(0.055)
Num of Obs.	46,860	46,860	42,600	42,600
Log Likelihood	-8752.975	-8579.913	-6992.699	-6962.097
AIC	17547.951	17231.827	14097.397	14056.194
County	✓	✓	✓	✓
Env. Controls		✓	✓	✓
Parcel Controls			✓	✓
Water Price				✓
Year				✓

Note: Table reports coefficients from multinomial logit models with time and parcel random effects. *Env. Controls* include groundwater depth, cumulative spring precipitation, and average max temperature in March-May. *Parcel Controls* add parcel size, annual delivered water if a parcel is in the delivery zone, distance to the coast, and lagged crop choice. *Water Price* and year are added to the final column. The baseline land use choice is fallow ground, which increases in magnitude over the sample period. Robust standard errors (clustered by parcel) are reported in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.3: Marginal Effects for an Increase TDS to 2,000 mg/L

	Sample Ave TDS 644 mg/L	(1) Margin TDS 2,000 mg/L	(2) Difference (pp)
Fallow Ground	10.6%	12.3%	↑ 1.7
		(1.04)	
Vegetable Row	30.6%	31.9%	↑ 1.3
		(1.70)	
Strawberry	22.1%	23.8%	↑ 1.7
		(1.09)	
Caneberry	20.5%	16.0%	↓ 4.5
		(2.73)	
Orchards	10.8%	10.3%	↓ 0.5
		(1.37)	
Nursery	5.19%	5.73%	↑ 0.54
		(0.72)	

Note: This table reports the predicted share of parcels in each crop type (in %) under a constant basin-wide TDS level of 2,000 mg/L, holding all control variables at their averages. Sample average Spring TDS is 644 mg/L. Standard errors are reported in parentheses.

Table 2.4: Willingness to Pay, for a 10 mg/L Reduction in TDS

	Willingness to Pay	Std. Error
Vegetables	$ 3,083.79	$ 1,242.74
Strawberries	$ 1,612.62	$ 977.85
Caneberries	$ 16,369.23	$ 7,369.70

Note: This table reports the estimated willingness to pay for a 10 mg/L reduction in TDS. Estimates are based on the panel mixed logit model presented in Column 4 of Table 2. Units are in dollars per acre. The standard error is calculated using the delta method.

Table 2.5: Marginal Effects: Robustness to Choice of Salinity Measure

	Sample Ave TDS 763 mg/L	(1) TDS 2,000 mg/L	(2) Chloride 300 mg/L
Fallow Ground	10.6%	12.3%	12.4%
		(1.04)	(1.30)
Vegetable Row	30.6%	31.9%	34.2%
		(1.70)	(2.00)
Strawberry	22.1%	23.8%	24.2%
		(1.09)	(1.19)
Caneberry	20.5%	16.0%	11.8%
		(2.73)	(5.07)
Orchards	10.8%	10.3%	11.5%
		(1.37)	(1.62)
Nursery	5.19%	5.73%	5.84%
		(0.72)	(0.73)

Note: This table reports the predicted share of parcels in each crop type (in %) under a constant basin-wide increase in chloride, holding all control variables at their averages. On average, chloride levels are 15% of TDS values, so an increase in chlorides to 300 mg/L is similar to a shift in TDS to 2,000 mg/L. Column (1) reproduces results from Table 2.3. Standard errors are reported in parentheses.

Table 2.6: Marginal Effects: Robustness to Exclusion of Delivered Water Zone

	Sample Average TDS 595 mg/L	(1) Margin TDS 1,559 mg/L	(2) Difference (pp)
Fallow Ground	10.6%	12.6%	↑ 2.0
		(1.07)	
Vegetable Row	27.9%	30.1%	↑ 2.2
		(1.59)	
Strawberry	16.2%	16.6%	↑ 0.4
		(0.96)	
Caneberry	25.8%	21.6%	↓ 4.2
		(2.50)	
Orchards	13.6%	13.9%	↑ 0.3
		(1.59)	
Nursery	5.95%	4.94%	↓ 1.01
		(0.64)	

Note: This table reports marginal effects from the estimation of our preferred panel mixed logit specification but restricts the sample to parcels located outside the Delivered Water Zone. Parcels located outside the DWZ have lower TDS values on average. We report the predicted share of parcels in each crop type (in %) under a constant basin-wide TDS level of 1,559 mg/L, holding all control variables at their averages, which is equivalent in percentage terms to the increase shown in Table 2.3. Column (2) reports the difference in percentage points from the sample average. Standard errors are reported in parentheses.

Chapter 3

Valuing Recycled Water for Irrigation: Direct and Indirect Benefits to Coastal Agriculture

3.1 Introduction

The stability of water resources for agricultural production has always been an important topic, but the scale and urgency of the issue has dramatically increased in recent decades. Climate change has brought warmer temperatures, shifts in precipitation patterns, sea level rise, and an increase in extreme weather events to agricultural regions globally (Nicholls and Cazenave 2010; Kunkel et al. 2013). Coastal regions are particularly at risk, since they often feature micro-climates conducive to the development of high-value crops that are difficult to grow in other locations. Rising temperatures and increased variability in precipitation can reduce the agricultural productivity of these delicate products, especially if the security of water resources is unknown. Water supply issues are magnified in coastal locations, as groundwater resources are subject to seawater intrusion, exacerbated by the overpumping of water (Wong et al. 2014).

If a region is reliant on groundwater that suffers from seawater intrusion, there are a limited number of strategies available to improve salinity conditions. Options hinge on actively reducing the amount of groundwater pumping or increasing the recharge of higher quality (lower salinity) water into the groundwater basin. [1] This may involve pricing groundwater or setting limits on extraction, building infrastructure that improves recharge, or finding additional sources of irrigation water. One emerging tool is to use treated municipal wastewater, or recycled water, to reduce the reliance on groundwater pumping and increase recharge to the underlying aquifer. As of yet, this is not a well-studied option, because there are

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[1] In the case of soil salinity, a common mitigation strategy is to increase the application of irrigation water, in order to leach salts past the root zone in the soil. This is not as effective of an option when the irrigation water itself is saline, as is the case with seawater intrusion.

limited micro-level water-use data available to credibly estimate individual grower impacts. In addition, recycled water itself is not typically of the highest quality, and is an expensive, "last-resort" solution that has not been implemented in many locations. However, in the uniquely profitable climates of coastal agricultural regions, recycled water has started to emerge as a potentially economically feasible adaptation strategy. Moreover, the possible benefits are expected to increase under climate change.

This paper rigorously investigates the viability of recycled water in a high-value coastal agricultural region as a mitigation strategy for drought and over-pumping of groundwater. I use predicted crop choices to estimate welfare changes due to recycled water access, using a panel mixed logit choice model. The crop choice model is also used to estimate the damages associated with high salinity conditions. I then examine the impacts that recycled water has on improving the underlying water quality of the aquifer, using staggered difference-in-differences and event studies. I evaluate the effects for growers that receive recycled water, as well as those who do not have access to recycled water, but farm in the same region. I then discuss conditions under which recycled water may be economically viable. To my knowledge, this is the first economic study of a real-world implementation of recycled water in agriculture.

The Pajaro Valley, located on California's central coast, offers this critical opportunity to estimate the effectiveness of recycled water. Best known for its berries and vegetables, this region has documented seawater intrusion issues since the 1950s, due to its dependence on groundwater for irrigation and its proximity to the coast. With its foggy, temperate climate, growers in the highly productive valley are motivated to find solutions that allow them to continue growing high-value, salt-sensitive produce. The local water management agency developed a groundwater pricing scheme to fund a recycled water program, delivering municipal treated wastewater from the nearby town to growers along the coast experiencing high salinity. As part of their duties, the agency has been extensively monitoring groundwater quality, pumping, land use, and delivered water. This includes a rich network of monitoring wells, which enables the observation and interpolation of water quality across space and time. While their production of especially valuable crops means that Pajaro Valley is an early adopter in using recycled water, this analysis provides a useful template for other coastal agricultural regions likely to suffer from seawater intrusion in the coming decades.

I find that small quantities of recycled water provide substantial benefits to the Pajaro Valley. Growers who receive recycled water deliveries are able to grow higher-value, salt sensitive crops at increased yields. Their direct benefits, at $16 million annually, are higher than the management agency's annual program costs. In addition, the groundwater quality beneath parcels that receive recycled water deliveries substantially improves, primarily in years where groundwater salinity is otherwise much higher than average. Neighboring parcels that do not directly receive recycled water deliveries also see their groundwater quality improve in years of high basin-wide salinity, although the effects attenuate quickly. Conservatively, these water quality benefits add up to an additional $10.8 million in high salinity years. While all growers benefit from the recycled water program's prevention of future seawater intrusion, the current beneficiaries of the recycled water program are growers located nearest to the coast.

Overall, this paper has two major contributions: (i) the first quasi-experimental, empirical assessment of the welfare effects from the implementation of a recycled water program, and (ii) the first study to propose and analyze recycled water as a mitigation strategy for salinity or groundwater overdraft. While there is no current economic literature on the implementation of a recycled water program, Ziolkowska and Reyes (2016) discusses socioeconomic factors that influence desalinization plant development. There are also several studies using survey methods to elicit a willingness to pay for recycled water or for products grown with recycled water. A few studies explore consumer concerns about the use of treated wastewater in agricultural production (Li, McCluskey, and Messer 2018; Savchenko et al. 2019). Menegaki, Hanley, and Tsagarakis (2007) surveys agricultural producers on their willingness to pay for recycled water of various quality in Greece, when faced with no restrictions in freshwater supplies. More closely linked to our work, Iftekhar, Blackmore, and Fogarty (2021) use contingent valuation and contingent behavior methods to elicit willingness-to-pay estimates for recycled water in water-constrained Perth, Australia, finding that agricultural users and horticulturalists have the highest valuation at $91 AUD/acre-ft.

Seawater intrusion is a growing problem for coastal agriculture, affecting many regions globally (Lee and Song 2007; Shammas and Jacks 2007; Tuong et al. 2003; Milnes and Renard 2004). There is a small but growing literature on the economic damages from saline irrigation water. Mukherjee and Schwabe (2014) conduct a hedonic analysis of farmland sales in California's Central Valley to estimate the marginal value of changes in groundwater salinity to irrigated agriculture. Rabbani, Rahman, and Mainuddin (2013) use survey methods in Bangladesh, examining severe damage to rice production due to a cyclone-induced seawater intrusion event. They find that average households lost 43-45% of their annual income, and salt-tolerant crops were not able to overcome the acute damage. Other research estimates salinity damages using structural approaches (Lee and Howitt 1996; Schwabe, Kan, and Knapp 2006; Connor et al. 2012; Roseta-Palma 2002; Knapp and Baerenklau 2006), since high-quality seawater intrusion data is limited. Currently, little research has been done to study ways to mitigate damages from salinity. There has been some work done to estimate the optimal groundwater extraction under seawater intrusion (Green and Sunding 2000; Reinelt 2020), as well as under saline soil conditions (Dinar and Knapp 1986).

Direct damages from groundwater overdraft can be tricky to measure, since depletion of an aquifer typically occurs over a long time horizon. There is excellent work on the externalities associated with extraction and water supply reduction (Brozović, Sunding, and Zilberman 2010; Pfeiffer and Lin 2012; Edwards 2016; Merrill and Guilfoos 2017). Other research is focused on the economic damages from land subsidence, where the land surface sinks due to reduced groundwater tables. Wade et al. (2018) studies land subsidence in Virginia, finding that coastal pumping invokes the greatest externality, but inland rural communities experience the highest damages. Several policies have been proposed to overcome this market failure, including water prices and markets (Smith et al. 2017; Ayres, Meng, and Plantinga 2021; Bruno and Sexton 2020) or restrictions on groundwater pumping (Drysdale and Hendricks 2018). While often effective mechanisms, water prices and restrictions are politically unpopular. This work proposes a new policy mechanism to reduce groundwater overdraft: recycled water as an alternative water supply.

Results provide valuable insights for coastal regions experiencing seawater intrusion, but also for other locations affected by water quality or supply constraints. With sufficient treatment, recycled water programs can provide an additional clean source of water to also combat soil salinity, or other types of groundwater contamination. In fact, 20% to 50% of irrigated agriculture worldwide is already negatively impacted by salinity (Pitman and Läuchli 2002; Assouline et al. 2015). Currently, there are recycled water facilities operating in California, Arizona, Texas, Florida, and Australia, and programs are being considered in water-stressed regions globally.

More broadly, this analysis has important policy implications for groundwater regulation. Many water basins around the world have already been stressed by persistent over-pumping of groundwater (Wada et al. 2010; Famiglietti et al. 2011). In California, groundwater issues are at the forefront of water policy debates, where on average groundwater accounts for 40% of the state's agricultural water supply. California's Sustainable Groundwater Management Act (SGMA) of 2014 requires overdrafted basins throughout California to reach and maintain long-term stable groundwater levels and correct undesirable outcomes associated with pumping over the next 20 years. The legislation includes specific mandates to local groundwater agencies to address seawater intrusion. Evaluating the possible benefits of an alternative water supply is critical to informing optimal groundwater regulation.

The paper proceeds as follows. Section 2 describes the background and policy context, while Section 3 describes the data and descriptive statistics. Section 4 outlines the crop choice model and results for estimating the direct benefits of recycled water. Section 5 presents the specifications and results for the indirect benefits of recycled water. Section 6 evaluates Pajaro Valley's program and discusses the feasibility of recycled water in other contexts. Section 7 concludes.

3.2 Background

Seawater Intrusion, Recycled Water, and Management

In coastal regions, underground freshwater aquifers and seawater are not typically separated by an impermeable boundary. Instead, they coexist, with the seawater underlying the freshwater, since the salts in seawater give it a higher density. The seawater "toe" describes how far inland the saltwater layer extends below the freshwater aquifer. Seawater intrusion takes place when the saline seawater mixes with the freshwater aquifer. This frequently occurs when irrigation tubewells are drilled and users pump groundwater at a rate faster than the rate of recharge; i.e. more water leaves the aquifer than enters from rainfall or agricultural runoff. When groundwater is overpumped, the pressure causes cones of depression to form, and seawater starts to enter the freshwater zones. This issue is exacerbated with sea-level rise, because the increased ocean pressure extends the seawater toe further inland, putting more of the aquifer at risk of seawater intrusion.

In the Pajaro Valley, seawater intrusion has been documented since 1951, shortly after irrigation tubewells were introduced in the region. With little rainfall during the primary growing season, and surface water making up 1.6% of irrigation water sources, almost all irrigation water is from groundwater pumping. On average, 55,000 acre-ft of water is pumped annually. This is nearly twice the sustainable yield of the basin, meaning that only half of the extracted groundwater is replenished through rainfall or from irrigation runoff. These groundwater withdrawals, combined with the proximity to the coast, have resulted in severe seawater intrusion. The extent of the intruded region has increased seven-fold since it was first documented. Seawater intrusion in the Pajaro Valley, on average, moves inland approximately 200 ft/year, and renders 11,000 acre-feet of water unusable annually (Wallace and Lockwood 2010).

The overpumping of groundwater and resulting seawater intrusion has led to salinity issues that currently impact crop production and threaten the stability of the basin's future water supplies. In 1980, the California Department of Water Resources listed Pajaro Valley as one of 11 water basins threatened by severe overdraft, out of 447 total basins (DWR 1980). The severity of the overdraft led to the development of the Pajaro Valley Water Management Agency (PVWMA) in 1984, to develop conservation programs and manage water resources. Under the Sustainable Groundwater Management Act, PVWMA has been tasked with bringing the groundwater basin into "balance" by 2040, such that groundwater extraction does not exceed water recharge into the aquifer. [2] While the management agency is encouraging water conservation in the form of improved irrigation efficiency, their main projects are in the development of alternative sources of water and promoting its recharge into the basin.

The primary source of alternative water supplies to combat seawater intrusion comes from a treated municipal wastewater facility built in the town of Watsonville, along with limited runoff from nearby wetlands. Both of these projects are limited in scale, and are described in more detail below. In total, they have the capacity to provide approximately 7500 acre-feet of water annually (AFY), which is equivalent to 13% of the annual groundwater pumping in the region, although annual deliveries have not yet exceeded 5500 acre-ft. The total annual quantity of recycled water delivered can be found in Figure 3.1. Since the recycled water program can only provide a limited amount of the irrigation water requirements of the Pajaro Valley, as a means to allocate the limited recycled water supplies, the agency created a "Delivered Water Zone" (DWZ). The boundaries of the DWZ are shown in Figure 3.2. Only users within this zone have access to the alternative water supplies. This region was targeted because the negative externality that groundwater pumping imposes is larger for growers directly on the coast than for growers further inland. Moreover, underlying hydrologic characteristics of the aquifer mean that groundwater pumping in the southern

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[2] PVWMA does have the authority to directly limit groundwater pumping, but that is not part of their current policy program. If the basin fails to come into balance by 2040, however, the Sustainable Groundwater Management Act will likely trigger pumping limits.

part of the region has a greater externality than in the north. The eastern boundary of the DWZ is Highway 1, rather than a particular aquifer feature. The benefits that the recycled water has in the DWZ are threefold: the higher quality water allows growers with saline groundwater to improve their crop yields, the alternative water supply reduces pumping on the coast, and the runoff from the application of this water helps to recharge the aquifer.

For most of the groundwater irrigation in the Pajaro Valley, growers bore individual tubewells on their property, rather than using canals or a shared water conveyance system. With the development of the recycled water program, the Delivered Water Zone needed a network of pipes, called the "Coastal Distribution System" (CDS) to move the recycled water to eligible growers. Construction began on the CDS in 2005, and has slowly increased over time. As of 2020, the CDS is approximately 20 miles long, and provides water to 5100 of the most severely affected agricultural acres. A map of the Coastal Delivery System can be found in Figure 3.3. Along the CDS, turnouts (essentially large water spigots), are installed in order to provide access to growers. In order for a grower in the DWZ to receive recycled water, the CDS needs to reach their parcel and have a turnout, the grower needs to submit an application, and there must be enough recycled water to meet both the needs of the current users and of the applicant.

Recycled water is sourced from the Watsonville Recycled Water Facility, which is a treated urban wastewater facility. It began operation in 2009. In the first full year of operation, the recycled water facility supplied 2700 acre-feet, but the facility has capacity for up to 6000 AFY, and plans have been approved to expand the facility further. While the recycled water is the main source of delivered water, there is some water available from the Harkins Slough Recharge and Recovery Facility. This facility intercepts some of the surface outflows from the Harkins Slough, which are wetlands just south of the Pajaro Valley. If not redirected for use in the valley, the outflow would have run into Monterey Bay, mixing with seawater. This storage facility has been in existence since 2002, and was the first groundwater recharge project constructed by the water management agency. While PVWMA has a permit to pump 2000 AFY from the Harkins Slough, the reality has been closer to 1000 AFY (with an actual delivered amount of approximately 160 AFY), due to a lack of flow through the Slough and the limited capacity in the recharge pond.

Since recycled water comes into contact with crops, proper treatment of the recycled water is paramount. In order to meet California's stringent recycled water standards, the water is tertiary treated, which means that all solids larger than 10 microns are removed, and the water is treated with UV light to kill pathogens. Some salts, nitrates, and phosphates may remain, but the quality is high enough to be directly applied to agricultural products, and safe enough to enter the aquifer for household use. [3] The average total dissolved solids (TDS) levels in recycled water is approximately 600 mg/L, which is high enough to cause some damage to salt-sensitive agricultural products, but much lower than TDS levels under drought conditions or in seawater-intruded wells. To ensure that salt contents are sufficiently

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[3] Not removing nitrates and phosphates is beneficial to agricultural producers, who may be able to reduce their fertilizer applications of these nutrients.

low, the recycled water is also blended with water from inland wells.

Water Pricing and Metering

To generate revenue to support the program, PVWMA collects augmentation fees for delivered water and fees for groundwater pumping in the basin[4]. The pricing of both groundwater and recycled water began in 2002, and a tiered pricing system was established in 2010. A snapshot of 2016-2021 water prices, by category, are found in Table 3.1. The price of water varies in the Pajaro Valley depending on where the water is sourced (delivered or pumped), if the well is metered or unmetered (residential pumps are unmetered), and if the well is within the delivered water zone. While fees for recycled water are higher than the cost of groundwater pumping in the DWZ, the fees are structured specifically such that when one factors in the electricity costs of pumping groundwater, the recycled water is slightly cheaper.

To price groundwater, PVWMA meters all wells capable of extracting 10 AFY, as well smaller wells, if they serves 10 acres of orchard, 4 acres of berries or row crops, or 2.5 acres of greenhouse facilities. Municipal, agricultural, and industrial wells make up 87% of water use, while rural residential wells make up 2%, and the rest is consumed by delivered water users. Few residential wells have meters, so they are estimated to use 0.5 AFY, and are charged based on that estimate.

Pajaro Valley's water prices are high, relative to other groundwater charges. In most of the United States, groundwater pumping is not metered, and water prices are merely the electricity costs required to operate the pump. Even in locations where water prices have been implemented, they tend to be significantly lower than the prices in Pajaro Valley. In California's productive Central Valley, water prices are commonly between \$70-150 per acre-foot, and the 2018 Farm and Ranch Irrigation Survey finds that California growers pay an average of \$67 per acre-foot for "off-farm" water. However, there are some regions facing similar or much higher water prices, depending on water supply constraints. Growers in San Diego county, for example, pay \$1700 an acre-foot, due to water scarcity. Moreover, in Pajaro Valley, the irrigation water costs are minor when compared to the revenue and profits for the crops grown in the region. On average, revenues are \$34,000 an acre, and reach up to \$68,000 per acre for strawberries. The combination of high revenues and low water requirements (around 2-3 acre-feet a year for most crops) leads me to believe that growers are not deficit irrigating in response to the water prices.

Agricultural Production

The Pajaro Valley is known for its production of delicate, high value produce, including strawberries, apples, raspberries, blackberries, artichokes, grapes, lettuce, and a variety of vegetables and herbs. As of 2019, total production value in the region was over \$1 billion

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[4] PVWMA has the ability to regulate and limit pumping directly, but has chosen to focus on the supplemental water projects and promotion of water conservation practices as alternatives to a command and control program.

across 28,500 irrigated acres. The major California berry producer Driscoll's is headquartered in the region, as is the cider producer Martinelli's. The temperate, coastal climate is ideal for the production of these crops. Moderate temperatures year-round, sunny days, and foggy nights are excellent growing conditions for sensitive crops. However, the delicate nature of this produce means that they are also susceptible to other challenges, such as salinity damage.

Salinity damage impacts almost all stages of plant growth and development, including germination, vegetative growth, and reproduction (Hu and Schmidhalter 2004). These effects lower crop yields and economic returns. For salinity in irrigation water, damages rarely occur until salinity reaches a crop-specific, critical "threshold". Then, crop yields decline linearly as salinity levels rise. The threshold at which salinity damages begin to occur varies significantly, depending on the crop. For example, strawberry yields begin to decline at TDS levels of around 450 mg/L, while zucchini may not decline in yields before TDS levels reach 2000 mg/L. Grattan (2002) estimates and compiles these thresholds and yield declines for a variety of crops grown in California. Figure 3.4 depicts the relationship between irrigation water salinity and yield for a subsample of crops in the Pajaro Valley.

Since crop revenues are so high for these products, even minor yield declines can lead to significant losses. In 2020, strawberry revenues were around $68,000 per acre, raspberries yielded around $59,000/acre, and apple revenues were $9,800 an acre. A yield loss of 10%, which would correspond to a TDS increase of 128 mg/L for strawberries, decreasing their revenue by $6,800 an acre. Therefore, growers are motivated to find possible solutions to deal with salinity issues in their groundwater, although individual basin management is out of their control. An alternative water source, such as recycled water, with moderate salinity levels, can mitigate severe crop losses while also preventing further seawater intrusion.

3.3 Data and Descriptive Statistics

Data provided from Pajaro Valley Water Management Agency for this analysis consist of water quality measurements from the network of monitoring wells, quarterly pumping and recycled water deliveries, depth to groundwater contour maps, and annual land use data. The details on how these data are built into a parcel-level panel are below. Additionally, I bring in variables on temperature and precipitation, property boundaries and ownership, and crop prices and revenue. Summary statistics are presented in Table 3.2.

Pajaro Valley Water Management Agency has been collecting water quality data in the basin since 1957, and has built a network of 286 monitoring wells. The locations of these monitoring wells are depicted in Figure 3.5 as black dots, overlaid on top of all the metered wells in Pajaro Valley (shown as light brown dots). These monitoring wells are typically sampled twice annually, once in spring (March-May) and once in the fall (September-November). This sampling method captures water quality at two critical time periods: (i) spring is before the primary irrigation season, after winter rains and when water tables are the highest, and (ii) fall is after the main irrigation season, when water tables are the lowest. While PVWMA takes multiple salinity measurements, I use the total dissolved solids (TDS) measurement, as it is generally the most salient to growers[5]. For both fall and spring of each year, I take all water quality measurements of TDS and use an inverse distance weighting technique to interpolate a map of water quality for the entire Pajaro Valley. In the analysis, I focus on spring TDS, given that salinity before the growing season is considered to be the most important for agricultural water users, and is the most likely to predict summer basin conditions for growers.

Figure 3.6 shows the history of average spring TDS values spanning 2003-2020, highlighting seasonal salinity patterns in the basin. Averages for the delivered water zone and the rest of the Pajaro Valley are compared. For the full region, spring TDS levels averaged 645.9 mg/L and ranged from 272.4 mg/L to 17,103.7 mg/L. The dashed line at 600 mg/L represents the approximate average TDS level of the recycled water. As can be seen, average salinity levels in the basin are frequently lower than the TDS levels of the recycled water, except in years of very high salinity. The spikes in salinity, which are especially high within the delivered water zone, are largely caused by drought conditions: groundwater pumping stays relatively stable, but the lack of precipitation leads to less groundwater recharge. With less freshwater percolating through to the aquifer, TDS levels in the remaining water are higher, and seawater intrusion is more likely to occur.

As outlined above, there is significant variation in salinity across time. Importantly for our analysis, there is also spatial variation in salinity. This spatial variation is largely driven by inherent underlying characteristics of the aquifer, as well as distance to the coast and surface water sources. Parcel characteristics, such as soil properties, slope, and land elevation also play a role. Figure 3.7 shows average salinity levels across the Pajaro Valley basin from 2009-2020, plotted by decile. This figure indicates that inland regions, aside from those located near the Pajaro River, experience significantly lower levels of salinity, especially towards the south. Notably, the coastal region just north of the delivered water zone experiences some of the highest TDS levels, providing some initial evidence that recycled water may be having an impact within the delivered water zone.

An impressive feature of the data from Pajaro Valley are the data on annual land use, which covers the 2009 and 2011-2020 growing seasons. PVWMA visually inspects and records land use on an annual basis. PVWMA also engages in quality control practices, including randomly sampling parcels for additional checks. These ground-truthed land use data have key advantages over satellite data, which is known to have substantial error in measuring land use among California's unique crop set (Reitsma et al. 2016; Alix-Garcia and Millimet 2020). Agricultural land use types include vegetable row crops, strawberries, blackberries and raspberries (caneberries), vine crops, artichokes, orchards, nursery crops, greenhouses,

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[5] Electrical Conductivity is highly correlated with total dissolved solids, and can typically be estimated from TDS using a simple conversion factor: 640 mg/L TDS = 1 ECw (dS/m), for ECw ¡ 5 dS/m. Chloride is a salinity measure linked specifically to seawater, and is one component of the TDS measure. We chose TDS to look at total salinity (including chloride), since other salts, such as those found in recycled water, impact crop production in the same way. We perform robustness checks in a salinity damages mixed logit model with chloride in Sears, Bruno, and Hanemann (2021).

fallow ground, cover crops, and unknown agricultural use. Non-agricultural land use types include residential, industrial, natural habitat, and other. For the analysis, I join artichokes with vegetable row crops, blueberries and vine crops with caneberries, and cover crops and unknown agricultural land with fallow ground, given the limited number of parcels in each of these categories. [6]

These detailed land survey data are coupled with tax assessor ownership and parcel boundary data from the County Assessor offices to form appropriate decision units. These data delineate property boundaries and enable assignment of land use and groundwater quality to each farm at the land parcel level, designated by the Assessor's Parcel Number (APN) in the tax assessor data. The average size of a parcel is 33.94 acres. I also use ownership data from the County Tax Assessor to aggregate parcels to the ownership level[7]. This helps both with crop decision-making (such as capturing crop rotation if it occurs), and with water attribution. Since not every parcel has a well or recycled water turnout, but almost all parcels use groundwater or recycled water, I want to assign that parcel water from the most likely source, which would be a well or turnout on another parcel owned by the same person.

The definition of "agricultural land" is therefore a parcel with documented ownership information that has been designated by PVWMA at some point to have produced a crop, and has known access to water. To be classified as having known access to water, the parcel must contain a well or a recycled water turnout, or the owner of the parcel has a different parcel with well/turnout access. In order to provide a comparison point on how restrictive this definition is, we look at the tax assessor land use classifications. After filtering out land uses that involve residences, businesses, and industry, across Santa Cruz and Monterey counties there are 1653 parcels that could plausibly be in agriculture. After restricting the dataset to parcels that also have a clearly linked source of water, I'm left with 1048 parcels. Therefore, this is a relatively restrictive set of qualifications. While this could lead to an overestimation of water applied per acre for the parcels classified as being in agriculture, as described below, there is no evidence that this is biased in a particular direction for growers receiving delivered water. Moreover, the difference-in-differences analysis and event studies do not use quantities of recycled water delivered in their analysis.

There are 978 documented wells across Pajaro Valley and 102 recycled water turnouts in the DWZ, all with quarterly measurements of how much water was pumped or delivered. For all of the wells owned by the same owner, I pool the total water pumped and area-weight the

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[6] In 2009, there was a large number of parcels labeled as "Unknown Agricultural Use" that may have corresponded to the time of sampling, which corresponds to a spike in "fallow" ground in that year. Robustness checks leaving 2009 out of the analysis lead to almost identical results.

[7] The data available on ownership vary slightly between Monterey and Santa Cruz counties. For Monterey, the owner's name(s) are listed, along with the share of the the parcel owned. For parcels with multiple owners, I use the parcel owner with the largest share as our "primary owner", and aggregate the parcels associated with their name. For Santa Cruz, owner names were not available, but mailing addresses were. Parcels are aggregated by their mailing addresses. Due to this limited information, if someone owns parcels in both Monterey and Santa Cruz counties, I am unable to link them together. Minor cleaning of names and addresses occurred to improve ownership matches.

water across all parcels planted in a crop during that year. I follow the same procedure for all turnouts owned by the same owner. This assumes that water needs across all crops are similar, which is largely the case for crops grown in the Pajaro Valley, which require between 2-3 acre-feet a year. I classify a parcel as using water if they are listed for an agricultural purpose that is not fallow. This includes "unknown agriculture". This does not include parcels that have no information on their agricultural status, making the assumption that PVWMA is capturing all agricultural fields.

I gather outside data to estimate crop prices and weather patterns. Data on temperature and precipitation are from PRISM Climate Data, which incorporates coastal weather patterns and land elevation into its projections. The data projections have approximately an 800 m resolution. I use the gridded data cell that lines up with the centroid of each of the parcels. I use averages of monthly mean temperatures and total precipitation in the spring of each year, at the parcel level. County Agriculture Commissioner Reports provide information on crop prices and revenue. Since several of the land use types include multiple crops, I take area-weighted averages of crop prices and revenue for each land use category, and average these across Santa Cruz and Monterey counties.

3.4 Direct Effects: Crop Choice Model

The following section evaluates the impact that recycled water has on growers that receive water deliveries using a discrete crop choice model. Growers receiving recycled water may see benefits of two forms: (i) their yields may improve with higher quality water, and (ii) they may be able to grow more salt-sensitive crops. To capture these benefits in tandem, I use a revealed preference, panel mixed logit model that evaluates the impacts of salinity and recycled water on crop choice, and calculates the willingness to pay for improvements in salinity. This framework also allows for a simulation to find the counterfactual crop choices without recycled water deliveries. The modeling framework, empirical strategy, and results of the model are detailed below.

Empirical Strategy

Spatially and time-varying data on groundwater quality, recycled water deliveries, and land use allow for the estimation of a panel mixed logit model to understand the impacts of salinity and recycled water on crop choices. The research design relies on observable changes in groundwater quality and recycled water deliveries, along with controls for observable and unobservable factors that may be correlated with both salinity, recycled water, and crop choice.

I take a similar approach to the working paper by Sears, Bruno, and Hanemann 2022 that estimates damages associated with groundwater salinity. Building on these methods, this approach differs in a few key ways. Most importantly, I consider only parcels that can be clearly linked to a source of water, since the analysis specifically accounts for recycled water deliveries. Additionally, part of the water assignment structure involves adding in tax assessor data to the model, and standard error clustering at the ownership level. This helps account for decision-making on crop rotations, allocation of water across parcels, and crop diversification that may occur. Finally, I allow for an unbalanced panel of parcels in agriculture: a parcel is able to leave agriculture and is still counted in the analysis up until the point of departure.

For each parcel i, a grower chooses a crop type j in year t. I assume the grower is profit maximizing and that each parcel produces a single crop (fallow ground, strawberries, vegetables, caneberries, orchards, or nursery crops). Profits for a given crop j depend on the output price p_{jt} and the crop yield Y_{ijt}. Crop yields are a function of groundwater quality s_{it}, recycled water deliveries w_{it}, and other factors to production Z_{it}. Production functions are assumed to be differentiable and exhibit diminishing marginal productivity to variable inputs, such that $\frac{\partial f_j}{\partial s_i} < 0$ and $\frac{\partial f_j}{\partial w_i} < 0$ for all $j = 0, .., K$, and $\frac{\partial f_j}{\partial s_i} \neq \frac{\partial f_k}{\partial s_i}$ and $\frac{\partial f_j}{\partial w_i} \neq \frac{\partial f_k}{\partial w_i}$.

A grower chooses the crop that yields the greatest profit. Therefore, across crop choices $j = 0, 1, ..., K$, the optimal crop choice is the one that yields the highest profit for given levels of s_{it}, w_{it}, p_{it}, and Z_{it}. I set the outside option $j = 0$ to be fallow ground, and normalize its profits to zero. The choice problem is:

$$\Pi_{it} = \max_{j} \left\{ \Pi_1^*(s_{it}, w_{it}, Z_{it}, p_{jt}), \ldots, \Pi_j^*(s_{it}, w_{it}, Z_{it}, p_{jt}), \ldots, \Pi_K^*(s_{it}, w_{it}, Z_{it}, p_{jt}) \right\} \tag{3.1}$$

The probability of choosing crop j in year t is therefore:

$$\rho_{ijt} = Prob[\Pi_j^*(s_{it}, w_{it}, Z_{it}, p_{jt}) > \Pi_k^*(s_{it}, w_{it}, Z_{it}, p_{jt})], \forall j \neq k \tag{3.2}$$

Profits can be estimated by:

$$\pi_{ijt} = \theta_j s_{it} + \omega_j w_{it} + Z_{it}'\gamma + \alpha p_{jt} + D_{jt}'\beta_i + \delta_t + \chi_c + \epsilon_{ijt} \tag{3.3}$$

where θ_j and ω_j estimate crop-specific impacts from changes in groundwater salinity and recycled water deliveries. γ is a vector of coefficients that captures the effects of parcel-specific characteristics on crop choice, including: parcel size, distance to the coast, temperature and precipitation, depth to the groundwater table, lagged crop choice, and water prices. The impact of lagged crop prices are described by α and assumed to be valued in the same way across parcels. D_{jt} is an indicator for the crop grown. In the mixed logit model, its coefficient, β_i is allowed to vary randomly and with parcel-level characteristics Z_{it}, w_{it} and s_{it}. The time trend δ_t captures linear basin-wide trends over time, and χ_c captures county fixed effects.

If the unobserved component, ϵ_{ijt}, is assumed to be distributed i.i.d. extreme value, and if the profits of the outside option are set at 0, then the probability of choosing the jth crop can be written as:

$$\rho_{ijt} = \frac{e^{\pi_{ijt}}}{\sum_{j=0}^{K} e^{\pi_{ijt}}} = \frac{e^{\pi_{ijt}}}{1 + \sum_{j=1}^{K} e^{\pi_{ijt}}}, \tag{3.4}$$

where the parameters can be estimated by maximum likelihood. The panel mixed logit structure model avoids invoking the Independence of Irrelevant Alternatives (IIA) assumption that troubles multinomial and conditional logit models (McFadden and Train 2000; Nevo 2000), which is particularly important in a setting with perennial crops and repeated observations over time.

The mixed logit model provides the framework for the direct welfare estimates of the delivered program. Under this structure, a simulation is run that estimates growers' crop choices if they did not have access to recycled water, and estimates welfare with and without the water deliveries. In addition, the estimates from the mixed logit model provide willingness-to-pay (WTP) estimates for improved water quality by crop, by dividing the marginal utility of reducing salinity by the absolute value of the parameter estimate on crop price α. Identification of the WTP hinges on the assumption that, conditional on the suite of relevant spatial and time-varying parcel-level observables and an annual time trend, unobservable factors are not correlated with both salinity levels and crop prices.

Identification Concerns

One potential concern with this analysis is that groundwater salinity may be endogenous to crop choice, if salinity is controllable by an individual farmer. While soil salinity problems can often be managed by an individual grower, provided that they have enough freshwater to leach salts out of the root zone, groundwater salinity is harder to influence. Groundwater salinity is largely based on unobserved hydrological and transmissivity properties of the underlying aquifer, along with recharge rates from precipitation and runoff, distance to the coast, and aggregate basin-wide groundwater pumping. In the crop choice model, I explicitly control for groundwater pumping, depth to groundwater, temperature, and precipitation.

It is also possible that basin-wide groundwater pumping may be influenced by other unobserved economic factors that also impact crop choice. I control for the distance to the coastline, since this is an important determining factor of soil texture and the spatial distribution of salinity in Pajaro Valley, and because coastal micro-climates determine how well crops grow in certain areas. Features of the parcel, such as its size and crop history, are also likely to influence planting decisions and could be correlated with salinity. The inclusion of a linear time trend accounts for basin-wide unobservables that may trend linearly with both salinity and crop choice over time. Finally, the inclusion of county fixed effects and time and parcel random effects can combat regional effects that may be correlated with salinity.

To identify the impacts of recycled water on crop choice, there may also be concerns about how recycled water is allocated. Conditional on being in the delivered water zone, assignment of recycled water is somewhat random: parcels that lie on the currently constructed portion of the Coastal Delivery System are the only parcels able to receive water deliveries. Growers apply for their recycled water turnout to be turned on. Application acceptance is conditional on whether there is excess recycled water available to serve the needs of all current users, and on underlying groundwater salinity. Recycled water availability depends on facility capacity, which has slowly increased over time. Finally, while underlying groundwater salinity does impact application acceptance, a parcel's groundwater salinity is not highly correlated with its impact on the aquifer salinity: i.e. the positive or negative externality from recycled water deliveries or groundwater pumping to neighboring parcels is not well-linked to a parcel's own salinity levels. This is especially important for the identification of the DiD and event studies, since salinity is explicitly controlled for in the crop choice model.

Finally, it's important to note that the outside option in the choice model is fallow land, rather than land that leaves agriculture. I drop parcels from the sample after they leave agriculture permanently. This is standard in the crop choice modeling literature, largely because it is difficult to think about comparing annual profits to a lump sum payment received when exiting agriculture. However, it does limit the model to thinking about relatively short-run effects of salinity damages. It is plausible that a grower experiencing dramatic increases in groundwater salinity may not believe that water quality will improve or that they will receive recycled water on a fast-enough timeline to remain in business. In the appendix, I use linear probability models to test this hypothesis, finding that increases to salinity are not significantly linked to parcels leaving agriculture.

Results

Results from the crop choice model are presented in Table 3.3. Column 1 shows the basic conditional logit estimates and Column 2 presents the mixed logit results, which is the preferred specification and has a lower AIC. The table reports crop-specific estimates of the effect of groundwater salinity, where salinity is measured as the total dissolved solids (1000 mg/L) from March-May of the growing season. In the mixed logit, the coefficients on the crop indicator variables are treated as random variables and are allowed to vary across parcels. Their coefficients and estimated standard deviations are also reported in the table, while coefficients on additional independent variables are suppressed. Standard errors are clustered by owner. I control for parcel-specific factors that directly affect salinity, including the depth to the groundwater table, groundwater pumping, the cumulative precipitation from March-May of the growing year, and the average mean daily temperature from March-May of the growing year. Also included are factors related to the parcel that may affect crop choice, including the parcel size, recycled water deliveries, distance to the coastline, and additional aggregate controls for agency's water pumping fee and a linear annual trend. All reported coefficients are relative to fallow ground, which increases in response to an increase in salinity.

Results demonstrate that, compared to fallow ground, an increase in groundwater salinity decreases the probability that a farmer will grow a high-value, salt sensitive crop. We see the largest effects among vegetables, strawberries, and caneberries, the most profitable and some of the most salt-sensitive crops grown in the region.

Since not all crops in our choice set are grown in the delivered water zone, the clearest way to evaluate the impact that recycled water has on crop choice is to look at the marginal effects of changes in salinity on crop choice for parcels that do and do not receive recycled water deliveries. These results are presented in Figure 3.8. Results are presented for each of the major crops that are grown both inside and outside of the delivered water zone, for three levels of TDS: 500, 1000, and 1500 mg/L. These are all relatively moderate levels of salinity: enough to impact yields, but not enough to completely destroy a crop. We see that parcels receiving water deliveries are much more likely to plant strawberries or nursery crops at all levels of salinity, and are slightly less likely to plant vegetables.

Anecdotally, when talking with growers in the Pajaro Valley, they stated that the recycled water is allowing them to grow strawberries in locations where the water quality was previously too poor. While this anecdotal evidence is clearly encouraging, I test this using the panel mixed logit structure by running a simulation that looks at how crop choices change for the parcels receiving delivered water if those deliveries no longer existed. I simulate and compute the annual utility-maximizing crop choices for each parcel under a scenario where there are no direct recycled water deliveries. To do this, I keep the estimated marginal utilities for the attributes of crops, parcels, and climate variables the same as in the panel mixed logit model in Table 3.3. For each parcel that currently receives recycled water, I estimate the probability of choosing each crop type and use these to predict each parcel's baseline crop choice. Then, the simulation recalculates the probabilities of each crop being grown for these parcels after removing the water deliveries to reflect the no recycled water scenario.

The differences in the estimated crop choice distribution is plotted in Figure 3.9, depicting which crops are chosen in the face of an elimination of recycled water. There is a dramatic increase in the amount of fallow ground, and significant declines in strawberry acreage and vegetables. There is an increase in nursery crops, which are the most salt tolerant. Caneberries and orchards are not frequently planted in the delivered water zone, and experience virtually no change.

To put the losses from planting lower value crops (or no crops) into dollar terms, I estimate how welfare shifts for growers who no longer receive delivered water. Following the procedure outlined by Small and Rosen (1981), where a change in welfare corresponds to the compensating variation for the removal of the recycled water program, expected welfare is defined as:

$$E[W_i] = \frac{1}{|\alpha|} \ln \sum_j \exp\left(\pi_{ijt}\right) \tag{3.5}$$

I estimate the welfare under the current scenario, and then re-estimate welfare with respect to the new predicted choices made under the program removal. The difference in welfare is shown in Figure 3.10. Across the subset of parcels that have received recycled water, there is a significant decline in welfare when the program is removed. This is expected, as growers are now required to use their highly saline water to produce crops, and make crop choices that are lower value but more robust to salinity, or choose to not grow a crop altogether. In total, I estimate that the direct welfare loss for growers no longer receiving recycled water amounts to \$176 million across 471 parcels. This translates to a welfare loss of approximately \$16 million annually, or \$1,867 per acre.

Finally, the estimates from the crop choice model allow me to estimate growers' willingness to pay (WTP) for a reduction in groundwater salinity. This is useful for the calculation of the indirect benefits, which estimates the impact that recycled water has on groundwater salinity. Knowing the WTP for improved groundwater quality allows me to calculate the benefits in dollar terms. To calculate the WTP, I focus on crops whose estimates in Table 3.3 were significant at the 95% confidence level or greater, namely, vegetables, strawberries, and caneberries. The willingness to pay estimates for a reduction in groundwater salinity of 10 mg/L are reported in Table 3.4, on a dollar per acre basis, as well as the 95% confidence interval of the estimates. While these willingness-to-pay estimates are wide-ranging, the high dollar values suggested by strawberries and caneberries indicate that growers highly value water with low salinity levels. The magnitude of these willingness-to-pay estimates are relatively high. Using the (Grattan 2002) estimates of crop responses to salinity, a 10 mg/L increase in salinity would be likely to decrease revenue for strawberries by approximately $446 dollars per acre, which is within the WTP range calculated here, but on the lower side.[8]

3.5 Indirect Effect Results: Impacts of Recycled Water to the Aquifer

The crop choice model above estimates the direct benefits to growers receiving recycled water deliveries, determining if growers are able to grow salt-sensitive, higher value crops. However, the model cannot capture the impacts of the recycled water on the underlying water quality. These impacts are paramount to understanding the effect recycled water has on mitigating seawater intrusion, and that benefits that may be gleaned by other users of the groundwater supply. I estimate these impacts in three ways. First, I conduct a simple, parcel-specific fixed effects regression, using the 2009-2020 data used in the same analysis as the crop choice model. Next, I use the extended water quality, recycled water, and water pumping data from 2003-2020 to estimate a staggered differences-in-differences model, where treated parcels are those that start receiving regular deliveries of recycled water. Finally, I implement an event study framework to evaluate how recycled water impacts water quality over time.

Empirical Strategy

Fixed Effects Model

I start by considering a simple fixed effects model for two reasons. First, I want to look at how marginal increases in delivered water impact groundwater quality. Secondly, it is worth looking at a specification that matches as closely to the crop choice dataset as possible, even if the subsequent regressions have a longer time horizon. The structure of the fixed effects

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[8] This back-of-the-envelope calculation assumes that salinity levels are above the threshold (450 mg/L) where strawberry yields are negatively impacted.

regression is:

$$\text{TDS}_{it} = \beta\text{Recycled}_{it-1} + \gamma\text{Well}_{it-1} + \rho\text{Temp}_{i,t-1} + \chi\text{Precip}_{it-1} + \delta\text{Crop}_{it-1} + \tau_i + \epsilon_{it} \quad (3.6)$$

where Recycled_{it-1} is the lagged annual quantity of delivered water to a parcel. As described in the data section, a parcel is assumed to have received delivered water if a turnout located within a parcel's boundaries receives delivered water, or another parcel owned by the same owner receives water from a turnout (which are designed to have the capacity to serve multiple parcels). All water that an owner receives is divided across all their parcels, area-weighted by the size of the parcel. I apply the same weighting methodology to Well_{it-1}, which is lagged pumped well water. We also lag spring average temperatures and precipitation (Temp_{it-1} and Precip_{it-1}, and include lagged crop choices and parcel fixed effects. Lagged crop choices are included since differences in management practices and crop characteristics may influence how water leaches through the groundwater system.

In an effort to construct a regression that is as similar as possible to the panel mixed logit model estimating damages from salinity, I estimate a regression without parcel fixed effects but including the same control variables implemented in the prior regressions:

$$\begin{aligned}\text{TDS}_{it} = \alpha + \beta\text{Recycled}_{it-1} + \gamma\text{Well}_{it-1} + \rho\text{Temp}_{it-1} + \chi\text{Precip}_{it-1} \\ + \delta\text{Crop}_{it-1} + \omega\text{Coast}_i + \lambda\text{Size}_i + \epsilon_{it}\end{aligned} \quad (3.7)$$

The basic fixed effects model provides a useful link to the crop choice model, and conveys important information about the impact of marginal changes in recycled water deliveries. However, this model does not take advantage of the full dataset or of the slow rollout of the recycled water deliveries. Therefore, I use staggered difference-in-differences and event studies to take a longer-term view of the recycled water impacts.

Staggered Difference-in-Differences Model

Water deliveries started in 2002, to three (of 102) turnouts, and slowly increased over time, as the recycled water facility was built and as storage capacity increased. The Coastal Delivery System broke ground in 2005, and has slowly expanded as funding becomes available. For example, an additional 700 acres were connected to the pipeline in 2020. Receiving recycled water deliveries is conditional on having a pipeline (and turnout), and enough system capacity to add a parcel's water needs to the system. Once a turnout starts delivering water, water deliveries continue to be delivered annually to the same parcel 96% of the time, effectively continuing to the treat the parcel over the course of the sample period. While recycled water deliveries have continued to increase over time, the majority of the turnouts were delivering some water by 2007. To determine the effect of recycled water deliveries on the underlying groundwater quality of the parcel, I begin by estimating the following difference-in-differences model under staggered adoption:

$$TDS = \beta Treated + \gamma Well_{i,t-1} + \rho Temp_{i,t-1} + \chi Precip_{i,t-1} + \delta Crop_{i,t-1} + \tau_i \quad (3.8)$$

where $Treated$ is an indicator that takes the value of one after a parcels starts received delivered water in a quantity of greater than 1 acre-ft a year[9]. For reference, the median quantity of delivered water to a parcel is 21 acre-ft. The coefficient β measures the difference in the change in Spring TDS for parcels that have received recycled water relative to the change in TDS for parcels that had yet to receive or never implemented water deliveries, after controlling for owner and time-varying factors that also correlate with salinity. In this way, β provides an estimate of the average treatment effect for treated parcels (ATT). This empirical approach allows for identification of the relationship between recycled water deliveries and annual changes in salinity, while also explicitly controlling for other confounding factors that are specific for each group of parcels owned, as well as for time-varying factors. Owner-by-year fixed effects are controlled for by τ_{it}.

The recycled water effect β is identified under the assumption that, after controlling for pre-trends, annual trends, and time-invariant owner characteristics, recycled water deliveries are as good as random. Equivalently, the annual salinity changes in parcels that had yet to receive recycled water are what the change in groundwater quality would have been for parcels who never receive delivered water.

Event Study

I next turn to an event study framework, as it can provide insight beyond staggered difference-in-differences, capturing the dynamic relationship between recycled water and groundwater salinity. Moreover, it has advantages in identification that staggered difference-in-differences methods may struggle with. Staggered DiD may not provide valid estimates of average treatment effects, since already treated units may effectively act as control units at later points in time. The estimated average treatment effect ends up as variance-weighted averages of several treatment effects (Goodman-Bacon 2021). An event study framework can modify which units act as controls, so that parcels receiving recycled water are not compared to those receiving water in the past (Baker, Larcker, and Wang 2021).

The setup of the event study is very similar to the staggered DiD, except that the difference-in-differences estimator is decomposed into $\bar{h} - \underline{h} - 1$ coefficients, as shown:

$$\text{TDS}_{ikt} = \sum_{h=\underline{h}}^{\bar{h}} \beta_h \text{Years Since}_{it}^h + \gamma \text{Well}_{it-1} + \rho \text{Temp}_{it-1} + \chi \text{Precip}_{it-1} + \delta \text{Crop}_{it-1} + \tau_{kt} + \epsilon_{ikt} \tag{3.9}$$

where

$$\text{Years Since}_{it}^h = \begin{cases} \mathbb{1}\{t \leq Treated_i + h\} \text{ if } h = \underline{h} \\ \mathbb{1}\{t = Treated_i + h\} \text{ if } \underline{h} < h < \bar{h} \\ \mathbb{1}\{t = Treated_i + h\} \text{ if } h = \bar{h} \end{cases} \tag{3.10}$$

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[9] There are twelve parcel-year observations that deliver greater than 0 acre-ft, but less than 1 acre-ft, which is (some percent) of the sample.

The individual coefficients show the impact of being h years out, relative to the initial delivery of recycled water. The endpoints $\underline{h}$ and $\bar{h}$ are binned to include all dates before $\underline{h}$ and after $\bar{h}$, in order to make sure that the treatment effects are identified separately from time trends. The event-time effects are identified under identical conditions as the difference-in-differences model.

In addition, I am interested in how aquifer water quality is changed for parcels neighboring those that receive recycled water deliveries, but do not directly receive delivered water themselves. In this case, Treated_i is equal to 1 when a neighboring parcel first starts receiving delivered water in excess of 1 acre-ft a year. Otherwise, the structure remains the same as in Equation 3.9.

Results

Fixed Effects Model

To evaluate the indirect effects of the recycled water program, I see how recycled water deliveries impact the quality of the underlying groundwater aquifer. First, I look at an exploratory fixed effects model, using largely the same structure and data as the crop choice model. All estimates can be found in Table 3.5. Generally, the significance and coefficients on the control variables are in line with expectations. Of note, using more pumped groundwater does not have a significant impact on an individual parcel's groundwater quality, which is important for the identifying assumptions of the crop choice model: growers do not have a significant individual impact on their own water quality.

The coefficients on the lagged delivered water are highly similar, but the estimation with the parcel fixed effects have higher standard errors. I weakly find that a one acre-ft increase in recycled water lowers groundwater salinity by 0.7 mg/L. While the signs (and slight significance) on the delivered water coefficients are encouraging, this is unlikely to be enough to make any sort of sweeping claim on the effectiveness of recycled water, much less use these estimates in further analysis of the cost effectiveness of the recycled water program. Therefore, we turn towards staggered differences-in-differences and event study methods.

Differences-In-Differences

The results from the difference-in-differences specification are presented in Table 3.6. Results suggest that a parcel that receives delivered water will see a 218.9 mg/L improvement in their water quality. This is a significant improvement, corresponding to approximately a 10% yield improvement in strawberries (if the salinity is higher than the 480 mg/L threshold), or a 5% yield improvement in orchard crops (if salinity is higher than the 640 mg/L threshold). This kind of improvement in water quality is both impressive and realistic, as salinity levels do vary that much from the beginning to the end of the growing season for many parcels.

While these results are encouraging, it is important to compare these results with the event study, to combat the concerns about the interpretation of staggered difference-in-differences methods. In addition, it allows us to see where the improvements are occurring in time, and whether or not they stay consistent.

Event Study

Results of the event study specification outlined in Equation 3.9 are shown in Figure 3.11. The overall treatment effect suggests that water quality improves by -239 mg/L after receiving recycled water deliveries. This is a similar magnitude as the DiD results, which had an overall treatment effect of -219 mg/L, and suggests that the staggered DiD results may not be overly biased. It is also useful to note the pre-trends in the event study, which are insignificant from zero, and are also an important identification requirement for the difference-in-differences estimates.

Perhaps the most striking results of the event study are the significantly negative spikes in years 7-9, as well as in year 15. On first glance, it is not immediately intuitive why treatment effects would be zero (or slightly positive) for the first six years, and then have a highly significant effect in improving water quality in year seven. However, when we look specifically at treatment timing and salinity levels in the region, the results fall into place. The median time in which an eventually treated parcel receives its first delivery is 2006. This means that on average, a parcel reaches treatment year seven in 2013, which corresponds to a massive increase in salinity in the delivered water zone, as shown in Figure 3.6.

Scientifically, this makes sense: recycled water is going to have a bigger impact in improving water quality in years when the groundwater salinity is exceptionally high, especially when the quantity of recycled water is a much smaller fraction than the water in the groundwater basin. Moreover, the average TDS of the recycled water is frequently higher than the average TDS level in the delivered zone, as depicted by the dashed line in Figure 3.6. In fact, the only years in which recycled water quality is much higher than the average aquifer quality is in 2012-2013 and 2020. Therefore, we would expect that recycled water would significantly improve underlying water quality in those years, which is what is reflected in the event study figure.

The results for the neighboring parcels are presented in Figure 3.12. This figure reports similar, but attenuated, findings to the water quality results directly underneath treated parcels. Across the board, confidence intervals are a bit noisier, but pre-trends are still at zero. The overall treatment effect is no longer significant, but water quality improvements up to 570 mg/L are reported in years 7-9 after the first recycled water deliveries. These effects are arguably the most interesting when considering the indirect benefits of the recycled water program. Although growers that receive recycled water deliveries still use some water from the underlying aquifer, growers without delivered water are the ones truly reaping the benefits from increased aquifer water quality.

I use the event study results for the neighboring parcels to make a back of the envelope calculation of the benefits of recycled water on the aquifer. This allows for the most conservative estimate: there is no “double-counting” of the benefits for producers who receive recycled water, and who may not use as much groundwater as those without recycled water supplies.

In years of high salinity, we see TDS levels substantially improve for neighboring parcels, up to 570 mg/L. According to the (Grattan 2002) estimates, a 500 mg/L reduction in TDS would translate to a 16% increase in vegetable yields or a 39% increase in strawberry yields. The WTP estimates calculated in the crop choice model say that this may have an impact of up to $123,000 per acre for vegetable producers and $86,850 per acre for strawberries. A more conservative approach would be to look only at changes in crop revenue for these crops. In crop revenue terms, a TDS improvement of 500 mg/L would have an impact of $14,345 on strawberries and $1,125 for vegetables per acre. For these neighboring parcels, benefits would add up to additional $10.78 million in benefits for strawberries and $1.52 million for vegetables. Of note, these are benefits that only accrue in years of especially high salinity.

3.6 Valuing Recycled Water in the Pajaro Valley and Beyond

Building a recycled water facility and distribution system from scratch is not a cheap undertaking. In the Pajaro Valley, the recycled water facility cost $24.5 million USD to build, and the construction of the delivery system has brought the total up to $48 million. Additionally, PVWMA faces $12 million in annual operating costs, which largely goes to facility operation, improvements, and maintenance, although this also includes the costs of personnel and basin monitoring. These annual costs are offset by the $12 million in revenue generated by the groundwater pumping fees and recycled water delivery fees.

In the direct benefits section, I find that without recycled water, producers would experience an average loss of $1,867 per acre. Largely, this seems like a reasonable estimate. On average, strawberry profits can reach up to around $12,000 in a “good” year. If strawberry yields were to be reduced by about 250 trays/acre (a 5% yield loss), that would correspond to a profit loss of approximately $2000. In total, these direct benefits from the recycled water were estimated to average $16 million annually, which is substantially higher than the annual water management agency costs.

I also find that in high salinity years, parcels neighboring those receiving recycled water could face benefits of $10.78 million for strawberries and $1.52 million for vegetables. These benefits are especially important because they reduce the negative impacts of extreme drought and salinity. These calculated benefits are short-run gains. However, there are also longer-term benefits that I cannot capture in this modelling framework: the reduction of seawater intrusion risk in areas that are not currently experiencing salinity issues. The added water to the basin and the reduction in pumping along the coast means that the eastern Pajaro Valley is less likely to experience seawater intrusion in the near future. While these benefits are difficult to estimate, this is likely to have impacts on long-term land values and crop yields.

In sum, recycled water has positive benefits to agricultural production in this region for three primary reasons. First, the value of the agricultural produce is significant: profits can reach $12,000 an acre, and crop revenues up to $80,000. Second, the crops grown in the region are very salt sensitive: a 168 mg/L increase in TDS can decrease strawberry yields by 10%. Finally, the Pajaro Valley experiences very high salinity conditions, such that the relatively saline recycled water is of a higher quality than seawater intruded wells. Due to the combination of these factors, a small-scale, relatively expensive recycled water facility provides substantial benefits to the region. For recycled water to be beneficial in other locations, a combination of similar factors will likely need to apply. However, there are some additional attributes that could reduce the overall costs of recycled water. Regions with larger neighboring municipalities may be able to provide higher quantities of recycled water at a lower cost. Furthermore, areas with canals or pipelines already in place, such as regions using surface water for irrigation, may be able to implement a recycled water delivery system with reduced infrastructure costs.

3.7 Conclusion

Coastal agricultural regions are facing several key issues under climate change: rising temperatures, increased precipitation variability, sea level rise, and a higher incidence of drought and extreme weather events. The interaction of these problems with limited groundwater supplies leads to the over-extraction of groundwater and seawater intrusion. Treated municipal wastewater is a promising strategy that can be used to prevent further groundwater overdraft and mitigate current damages from salinity. Through its use as an alternative water supply, growers can directly use this water on their fields, reducing their reliance on constrained groundwater resources and preventing further seawater intrusion. For growers facing highly saline groundwater, the recycled water can also serve as a higher quality water source, allowing for the production of more salt-sensitive crops and increasing yields.

While recycled municipal water is a promising concept, and programs are starting to be implemented in water-stressed regions, there is little economic research on the impacts of recycled water to growers. This study explores the value of recycled water in two ways: (i) the welfare gains for growers directly receiving water deliveries, through higher-value crop choices and improved yields; and (ii) changes in the underlying aquifer quality below the recycled water delivery area, to evaluate indirect impacts of recycled water. To study the direct effects of recycled water on crop choices and welfare, I use a panel mixed logit choice model. The structure of this approach allows for simulations of grower decisions in the absence of a recycled water program and estimates of the willingness to pay for changes in groundwater salinity, while capturing heterogeneity in crop choice decisions. To evaluate the impacts of recycled water on aquifer salinity, I use staggered difference-in-differences and event studies, given the slow ramp-up of water deliveries over time.

I find that growers receiving recycled water are less likely to leave their ground fallow, and are more likely to plant high-value, salt sensitive crops, such as strawberries. Welfare gains for producers directly receiving water deliveries add up to $16 million annually for 5500 acre-ft of delivered water. I also find that recycled water improves the water quality of the underlying aquifer. The effects are strongest directly underneath parcels receiving recycled water, and are driven by years where salinity levels are highest. Neighboring parcels that do not receive water deliveries only see improvements in water quality in high-salinity drought years. Since recycled water also has non-negligible salinity levels, improvements to water quality are negligible or non-existent in years of high rainfall.

Altogether, these welfare gains are a conservative estimate for benefits to agricultural producers. I look at immediate benefits to agricultural producers, as they make crop choice decisions in a saline, water-constrained environment. This study does not capture the full effects of the additional water supply in preventing longer-term seawater overdraft. For example, farmland further away from the delivered water zone may be able to avoid severe seawater intrusion in upcoming decades due to the recycled water program, although their current salinity levels may not change. However, the findings of improvements in water quality directly on the coast do serve as promising indicators that future seawater intrusion is being at least partially managed. While beyond the scope of this paper, if hydrologic models were used to estimate individual well-level externalities, a basin-wide model of improvements in water quality may be estimated.

The combination of Pajaro Valley's high value crops and temperate coastal climate means that they are willing to invest in expensive programs to maintain agricultural production in the region. However, the future of using municipal treated wastewater as an additional water source is expanding rapidly. There are 250 small-scale recycled water programs in California alone, with others in Arizona, Florida, and Texas. Moreover, there is a promising future for recycled water in locations such as in South Korea, where groundwater overdraft has led to seawater intrusion in 41-50% of coastal groundwater sources (Lee and Song 2007). Recycled water has a three-fold benefit in our setting and in many other coastal regions, where it provides an additional water supply, improves water quality, and prevents seawater intrusion. However, in the face of future drought and limited freshwater availability, the benefits of an additional water supply may alone be enough to justify the costs of a recycled water facility in arid regions worldwide. Regardless, recycled water may play a major role in climate change mitigation strategies for coastal regions in the future.

Figure 3.1: Annual Recycled Water Deliveries

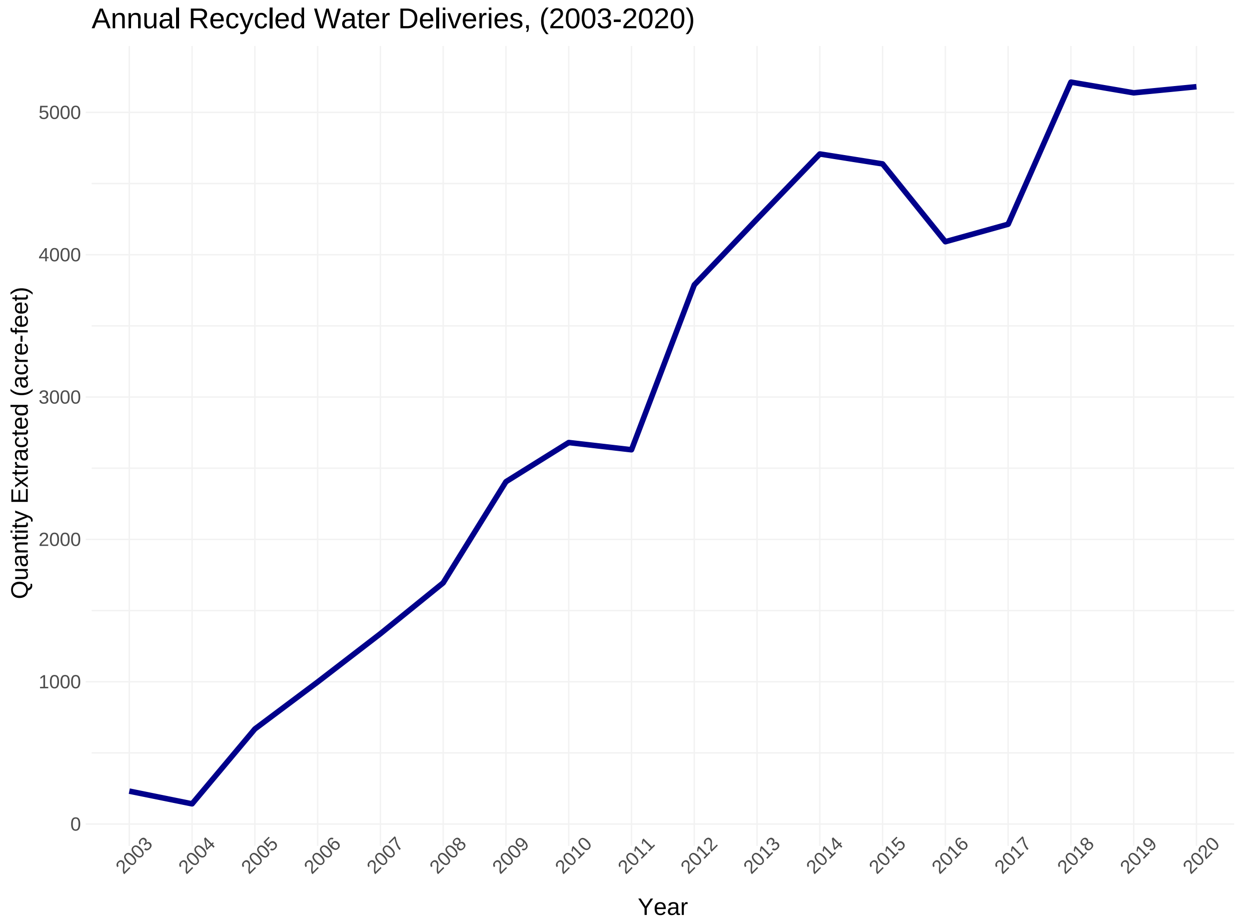


Figure 3.2: Pajaro Valley's Delivered Water Zone

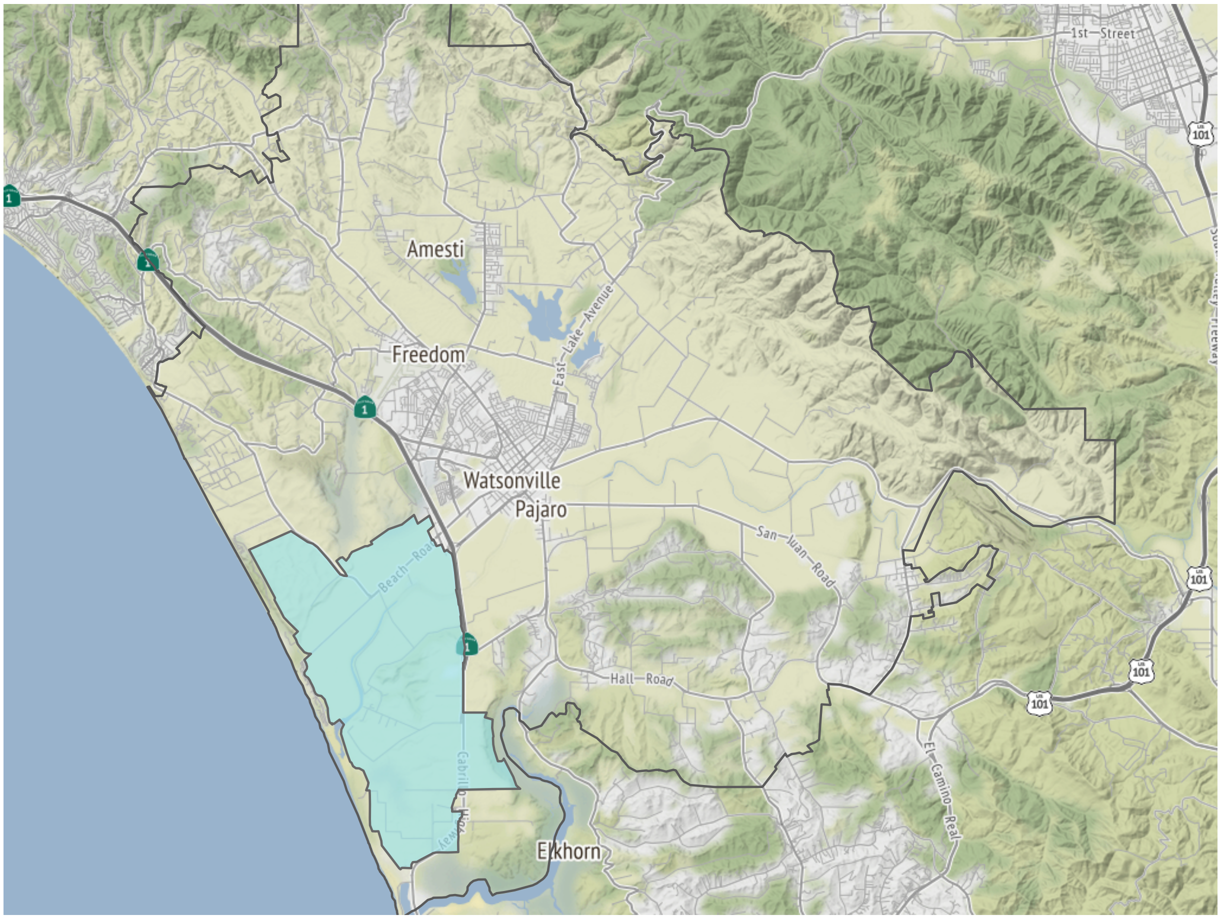
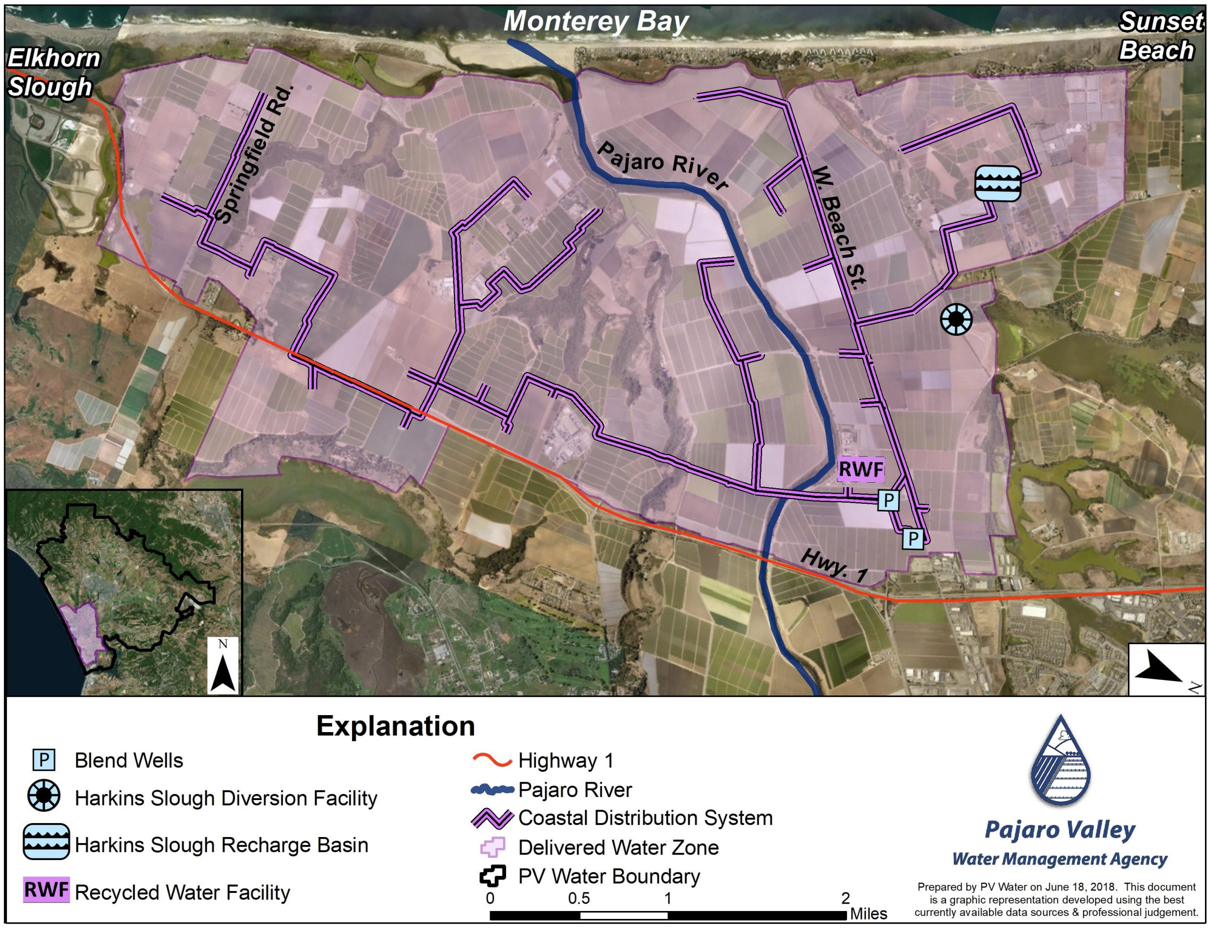
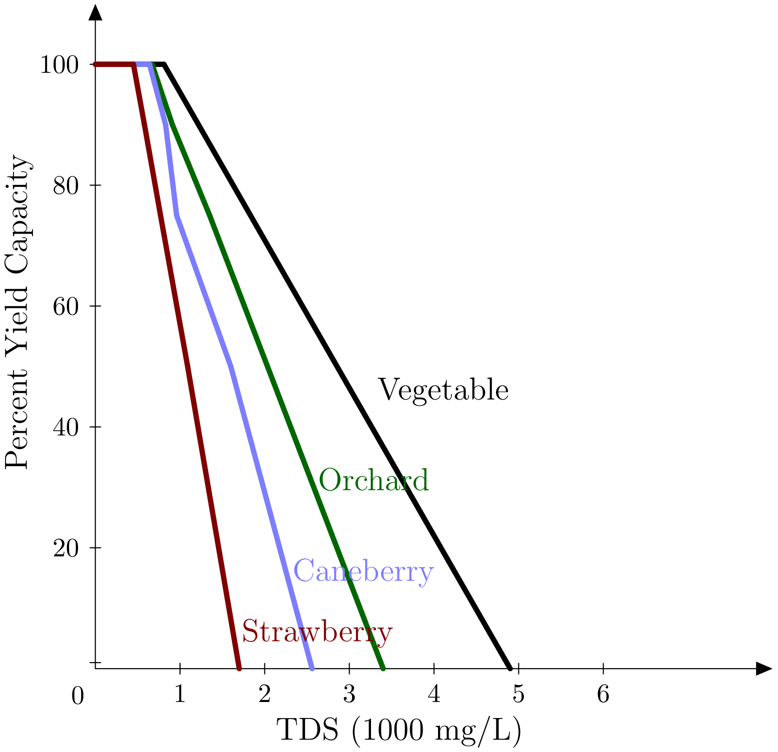


Figure 3.3: Pajaro Valley's Coastal Distribution System (Source: PVWMA)



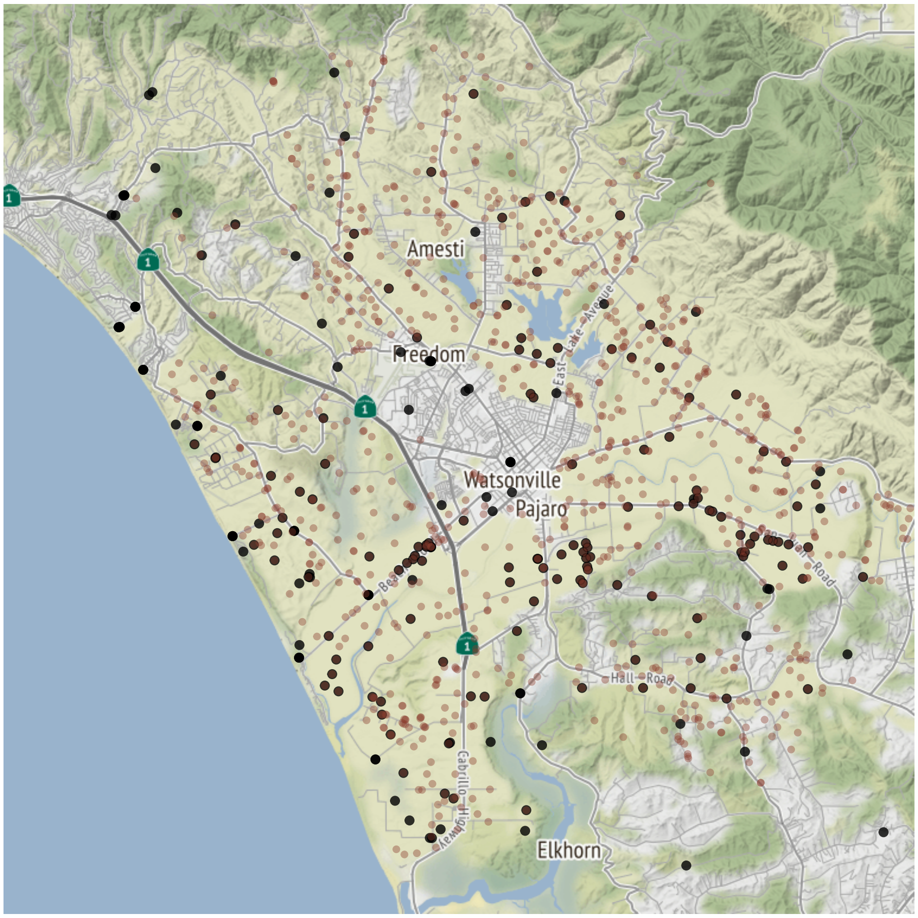
Prepared by PV Water on June 18, 2018. This document is a graphic representation developed using the best currently available data sources & professional judgement.

Figure 3.4: Decline in Crop Yields Due to Salinity



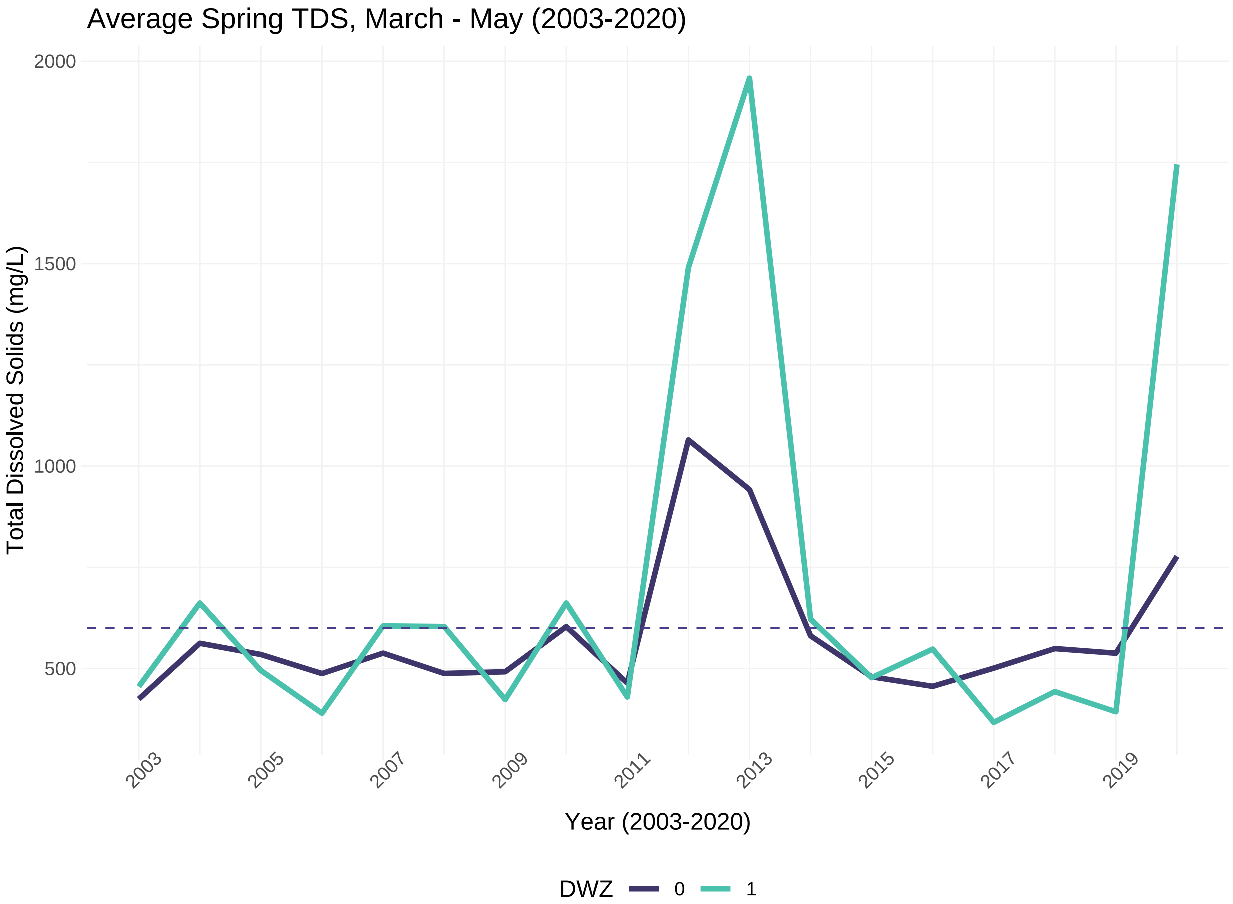
Source: Sears, Bruno, and Hanemann (2021).
“Caneberry” includes blackberries, raspberries, blueberries, and vine crops, while “orchard” refers to apples.

Figure 3.5: Metered and Monitoring Wells, Pajaro Valley, CA



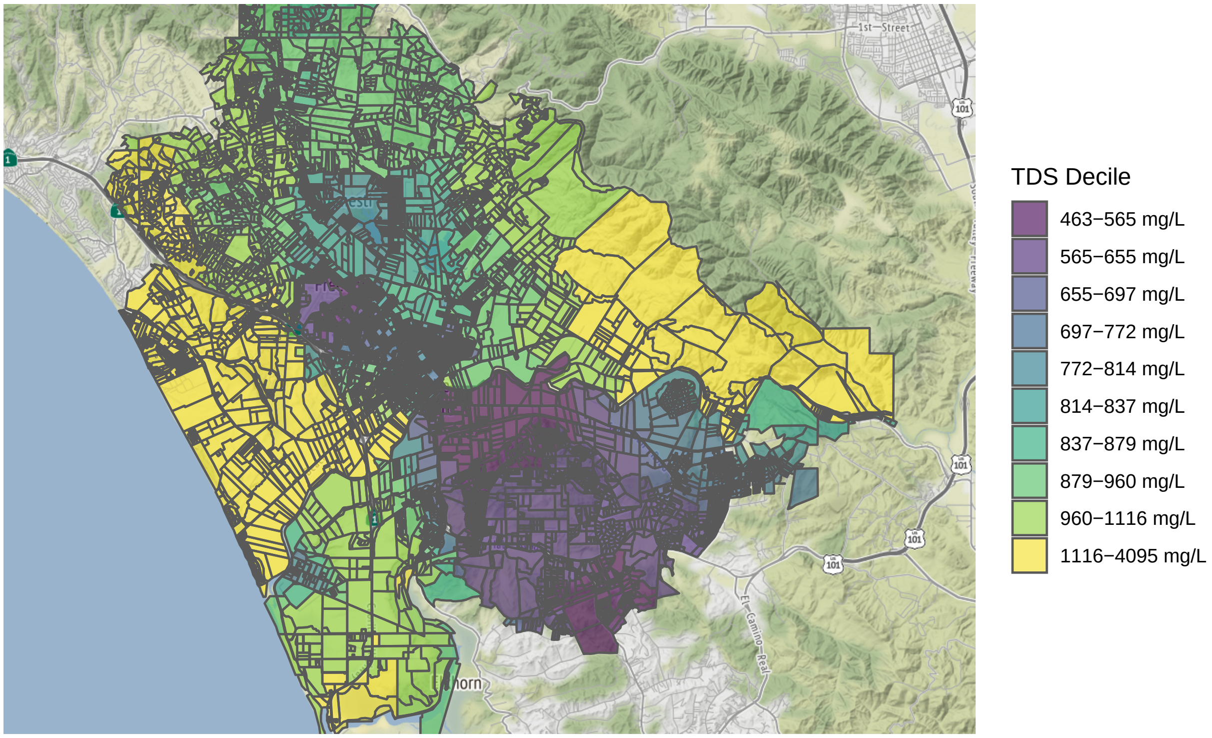
Note: Each light brown point depicts the location of a metered well in the Pajaro Valley, while each black dot represents monitoring wells used by PVWMA to determine water quality.

Figure 3.6: Average Spring Total Dissolved Solids (March-May), 2003-2020



Note: Figure shows average parcel-level spring TDS (mg/L) in groundwater from 2003 to 2020.

Figure 3.7: Spatial Variation in Total Dissolved Solids (TDS)



Note: The figure maps the average TDS (mg/L) from 2003-2020 for all parcels in the water agency service area. Values are interpolated from observations at monitoring wells and averaged across time. Each color represents a decile of average TDS.

Figure 3.8: Marginal Effects of the Crop Choice Model, by Crop and by Water Source

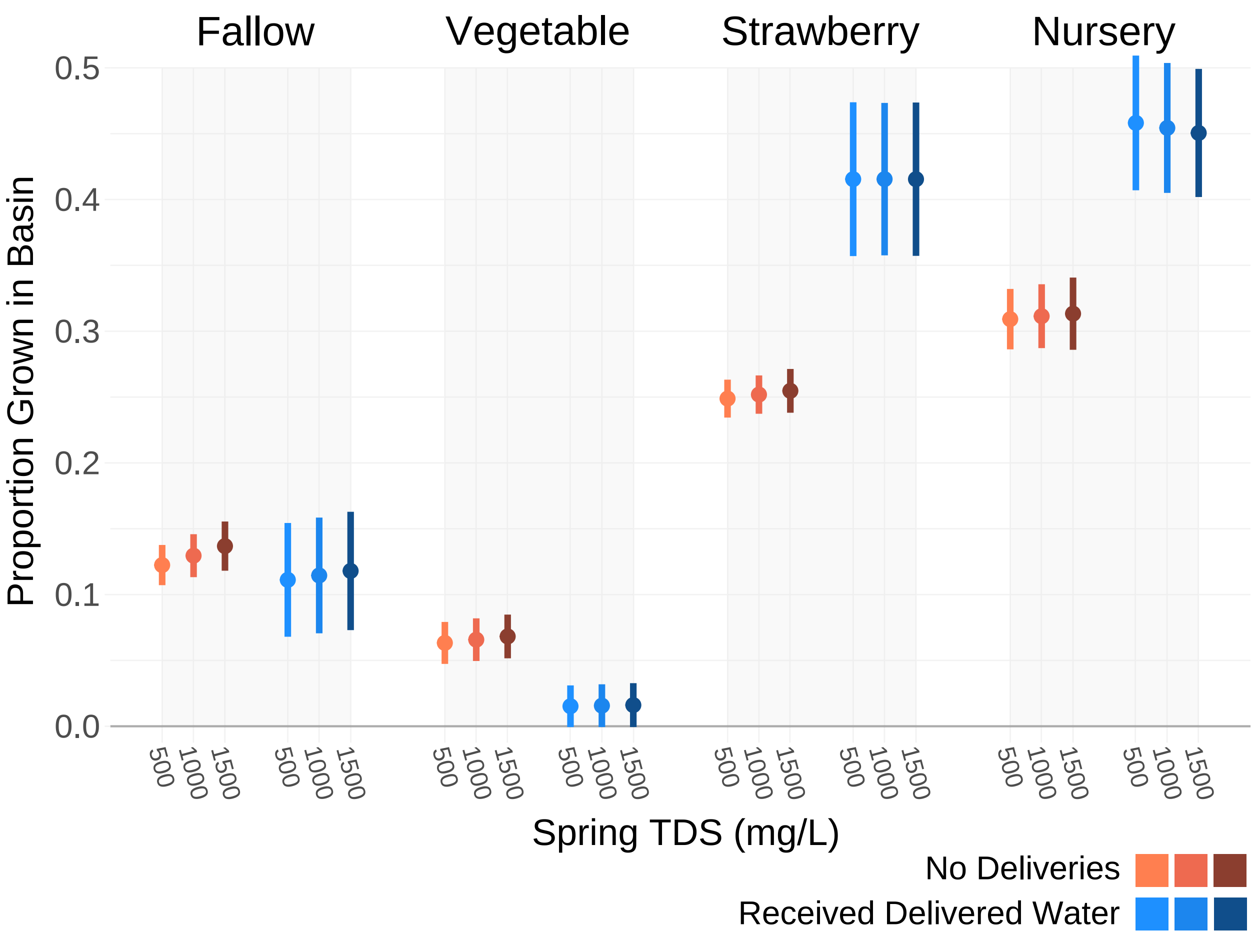


Figure 3.9: Estimated and Simulated Changes in Crop Choice under Removal of Recycled Water Program

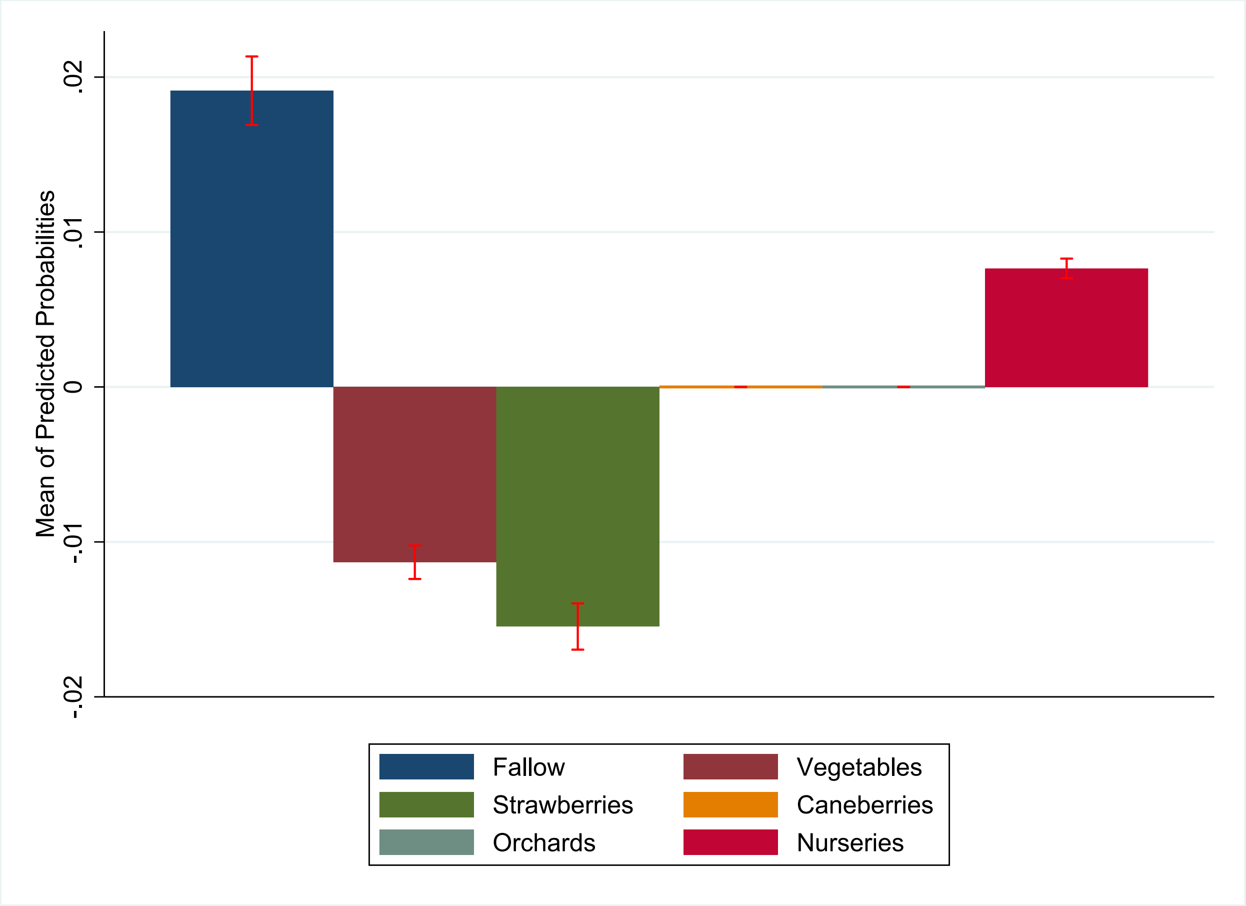


Figure 3.10: Kernel Density of Welfare with and without Recycled Water Program, for Parcels Receiving Delivered Water

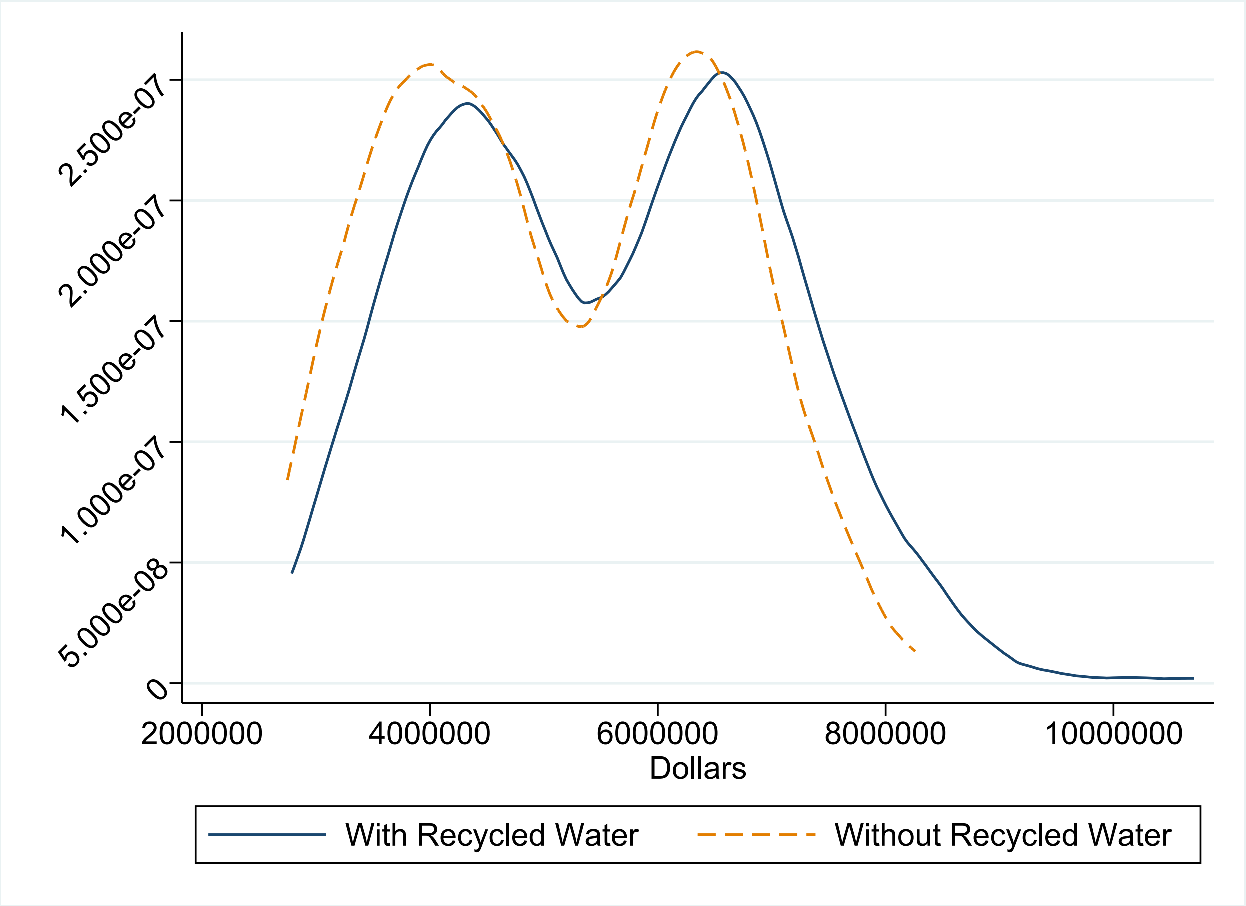


Figure 3.11: Event Study Results

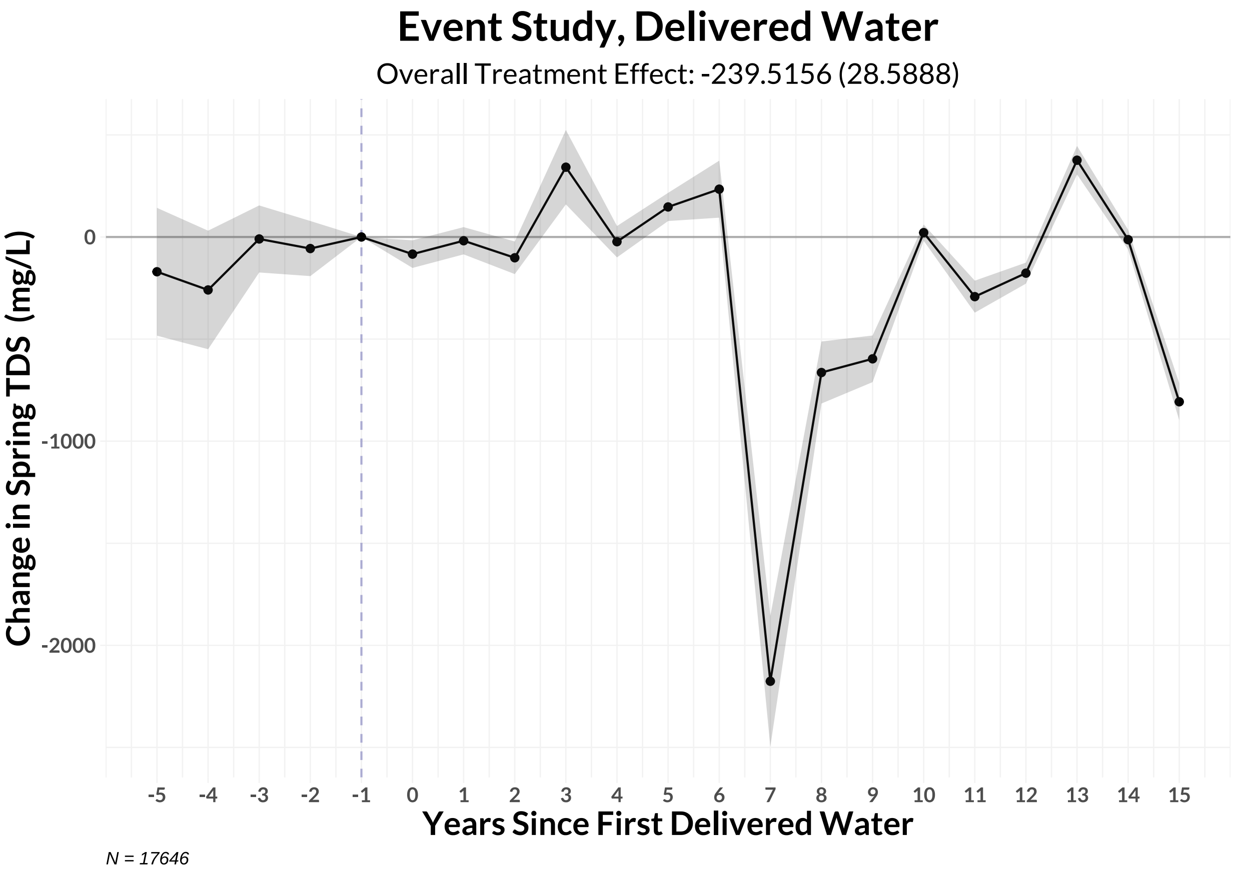


Figure 3.12: Event Study Results: Parcels Neighboring those Receiving Recycled Water

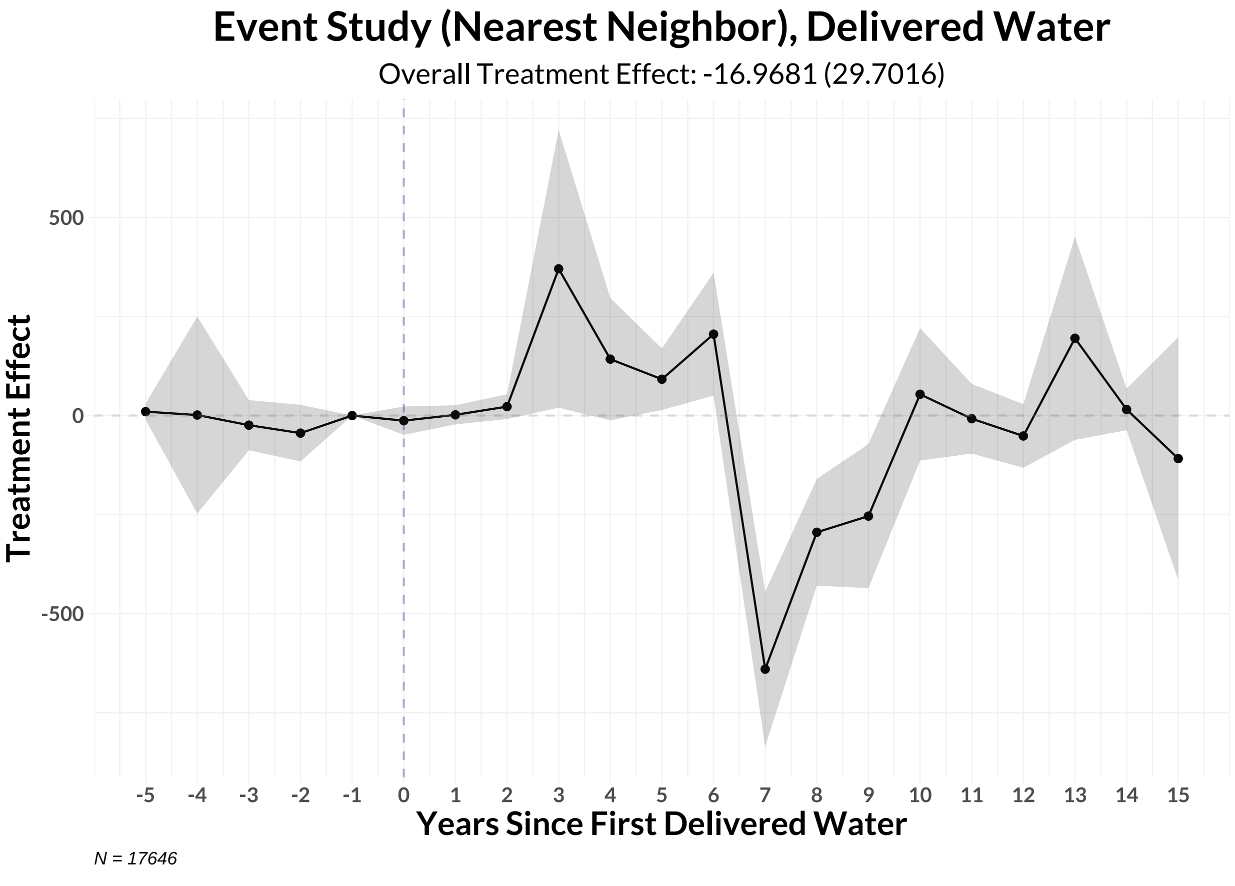


Table 3.1: Water Prices in Pajaro Valley, Dollars/Acre-ft

Year	Recycled	GW Pumping (in DWZ)	GW Pumping (outside DWZ)	Residential
2016/17	359	258	203	97
2017/18	369	282	217	103
2018/19	381	309	231	109
2019/20	392	338	246	115
2020/21	392	338	246	115

Table 3.2: Descriptive Statistics

	Mean	SD	Min	Max
Parcel Characteristics (parcel-year, 2003-2020)				
Total Dissolved Solids (mg/L)	598.620	710.170	268.762	17,103.720
Temperature (C)	13.047	0.930	10.813	15.781
Precipitation (mm)	140.192	85.720	7.768	419.035
Pumped Groundwater (AF)	29.164	56.977	0	1,106.819
Recycled Water Deliveries (AF)	8.961	23.692	0.000	229.119
Distance to Coast (meters)	28,029	4,174	24,411	31,249
Parcel size (ft^2)	1,476,116	3,305,805	94	51,618,600
Parcel Characteristics (parcel-year, 2009-2020)				
Depth to Groundwater (ft)	-2.309	6.679	-5	0
Fallow	0.13	0.34	0	1
Vegetable Row	0.31	0.46	0	1
Strawberry	0.25	0.43	0	1
Caneberry	0.17	0.38	0	1
Orchards	0.071	0.26	0	1
Nursery	0.064	0.24	0	1
Prices (region- and basin-year, 2009-2020)				
Groundwater Assmt. Fee ($/AF)	201.04	55.98	80	338
Vegetable Row price ($/acre)	10,722	1,614	8,441	13,113
Strawberry price ($/acre)	67,164	7,697	54,029	78,387
Caneberry price ($/acre)	55,773	6,686	42,492	71,308
Orchard price ($/acre)	206,497	571,273	6,854	1,914,633
Nursery price ($/acre)	223,260	65,653	131,740	358,359

Note: This table reports summary statistics for parcel- and basin-level characteristics. Land use and depth to groundwater data are only available from 2009-2020, while the rest of the time-varying data are from 2003-2020. Reported TDS measurements are interpolated observations taken in the spring of each year (march-May). Precipitation is cumulative and temperature represents the average daily maximum, both from March-May of the growing year. Summary statistics for groundwater pumping and water deliveries reflect averages only for parcels that contain a well and/or a water turnout. Distance to the coast is calculated with CA's official boundary. Groundwater depth is measured in feet above mean sea level; negative values reflect feet below sea level. Land use is expressed with dummy variables equal to 1 if the majority of that parcel is planted in that crop. "Caneberries" include blackberries, raspberries, and blueberries and "orchards" include apples and vineyards.

Table 3.3: Crop Choice Model

	Cond. Logit	Mixed Logit
Ave Price$_{t-1}$	5.58e-07***	4.25e-07***
	6.96e-08	(1.74e-07)
Vegetable	7.13***	3.13*
	(1.14)	(1.67)
Strawberry	11.58***	9.29***
	(1.08)	(1.38)
Caneberry	-6.96***	-13.92***
	(1.74)	(2.97)
Orchard	-16.96***	-10.44*
	(2.72)	(5.72)
Nursery	4.86**	2.99
	(1.92)	(3.63)
Vegetable SD		1.48
		(0.13)
Strawberry SD		0.83
		(0.12)
Caneberry SD		2.95
		(0.19)
Orchard SD		6.02
		(0.59)
Nursery SD		4.55
		(0.47)
Vegetable TDS	-0.040	-0.093*
	(0.036)	(0.051)
Strawberry TDS	-0.085**	-0.065*
	(0.036)	(0.040)
Caneberry TDS	-1.38***	-0.55**
	(0.26)	(0.26)
Orchard TDS	-1.91	-0.38
	(-1.91)	(0.31)
Nursery TDS	-0.00061	0.046
	(0.037)	(0.050)
Num of Obs.	55278	55278
Log Likelihood	-12299.013	-9462.3503
AIC	24720.027	19066.701

Regressions are discrete choice models, looking at land use choice by parcel. The baseline land use choice is fallow ground, which increases in magnitude over the course of our sample period. All models include controls for lagged water deliveries, lagged pumping volumes, lagged crop choice, depth to groundwater, water price, temperature, precipitation, parcel size, distance to the coast, year, and county fixed effects. Robust (clustered by owner) standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3.4: Willingness to Pay, for a 10 mg/L Reduction in TDS

	Willingness to Pay 10 mg/L reduction	Std. Error
Vegetables	$ 2,476	$ 991
Strawberries	$ 1,738	$ 851
Caneberries	$ 13,137	$ 5,564

Note: This table reports the estimated willingness to pay for a 10 mg/L reduction in TDS. Estimates are based on the panel mixed logit model presented in Table 3.3. Units are in dollars per acre. The standard error is calculated using the delta method.

Table 3.5: Effects of Delivered Water on Groundwater Salinity, Fixed Effects Estimation

	Dependent variable:	
	Spring TDS (mg/L)	
	(1)	(2)
Well_{t-1}	0.032	0.399
	(0.216)	(0.369)
Recycled_{t-1}	-0.760^{*}	-0.709
	(0.409)	(0.455)
Spring Precip_{t-1}	1.217^{***}	1.760^{***}
	(0.222)	(0.161)
Spring Temp_{t-1}	-101.439^{***}	-46.785^{***}
	(10.088)	(8.748)
Depth_{t-1}	0.247	-17.056^{***}
	(1.551)	(1.658)
Area	0.00002^{**}	
	(0.00001)	
Distance to Coast	-0.041^{***}	
	(0.008)	
Water Price_{t-1}	-1.646^{***}	-1.315^{***}
	(0.481)	(0.235)
Vegetables_{t-1}	98.184^{**}	114.481^{***}
	(44.814)	(42.131)
$\text{Strawberries}_{t-1}$	78.934^{*}	113.162^{***}
	(47.459)	(42.703)
Caneberries_{t-1}	2.630	141.837^{***}
	(39.712)	(39.665)
Orchard_{t-1}	-216.297^{***}	89.778^{**}
	(53.580)	(42.004)
Nursery_{t-1}	183.451^{*}	272.837^{*}
	(100.302)	(165.255)
Constant	$3,259.140^{***}$	
	(265.128)	
Parcel FE		X
Observations	9,370	9,370
R^2	0.074	0.322
Adjusted R^2	0.073	0.226
Residual Std. Error	924.527 (df = 9356)	844.981 (df = 8207)

Note: Regressions evaluate how groundwater salinity (measured by Total Dissolved Solids) changes with increases in delivered, recycled water. The control variables and time horizon match the crop choice model presented in Table 3.3. *p<0.1; **p<0.05; ***p<0.01

Table 3.6: Effect of Delivered Water on TDS

Dependent Variable:	SpringTDS
Model:	(1)
Variables	
Treated	-218.9***
	(38.97)
Well_{t-1}	0.0966
	(0.1549)
Temp_{t-1}	-41.59
	(74.04)
Precip_{t-1}	-0.0770
	(0.4248)
Fixed-effects	
Year×Owner	Yes
Fit statistics	
Observations	17,646
Adjusted R^2	0.71605

Two-way (County & Year) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

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