# ASSESSING WATER SCARCITY ADAPTATION:

# INSIGHTS FROM COLLECTIVE INVESTMENTS AND GLOBAL POLICY SPILLOVERS

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## ABSTRACT

The management of surface and groundwater is a crucial component in ensuring the resilience of agricultural production, both globally and in the Western U.S., especially as the effects of climate change continue to intensify widespread and unprecedented droughts. Most of the water in the Western US is managed and distributed by irrigation organizations (IOs). In 2018, these entities served 55.5% of the total irrigated acres in the West. Although previous studies have focused on farm-level adaptations, very little is known about the investment decisions made by IOs in the adoption of adaptation strategies; this literature gap represents an urgent and understudied element in drought adaptation, especially as delays in off-farm action may compound long-term vulnerability to drought. This study empirically evaluates IO long-run adaptations to water scarcity in the Western region, exploring differences in adaptation investments based on past experiences of water scarcity and organizational characteristics. We find evidence indicating that while water scarcity experience is a driver of some adaptations, other characteristics display a higher association with adaptation likelihood. We uncover a non-linear relationship between organization size and adaptation likelihood, and a positive relationship between eligibility for federal support programs and adaptation investments.

Groundwater depletion also presents a growing threat to agricultural systems worldwide. This study focuses on California, as the state's most valuable crops, tree nuts, both rely on and contribute to rapid groundwater depletion. The 2014 Sustainable Groundwater Management Act (SGMA) mandates sweeping reductions in groundwater use by 2040. Under the assumption that reductions in irrigated acreage will translate to

decreased exports, we present a descriptive exercise assessing potential spillover effects of SGMA on global water use through virtual water exports. By estimating changing virtual water flows, this analysis broadens the discussion of Western U.S. water scarcity adaptations to consider potential global spillovers.

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# CHAPTER I

# IRRIGATION ORGANIZATIONS IN THE WESTERN US: ADAPTING TO WATER SCARCITY

*The data utilized in this research were derived from the 2019 Survey of Irrigation Organizations (SIO), collected by the National Agricultural Statistics Service (NASS), United States Department of Agriculture. Any interpretations and conclusions derived from the data represent author viewpoints and are not necessarily those of NASS. The analysis, interpretation, and conclusions presented herein are those of the author and have not undergone review by NASS.*

# 1. ABSTRACT

The management of surface water is a crucial component in ensuring the resilience of agricultural production in the Western U.S., especially as the effects of climate change continue to intensify the unprecedented droughts and water scarcity impacting this region. Most of the water in the Western region is managed and distributed by irrigation organizations (IOs). In 2018, these entities served 55.5% of the total irrigated acres in the West. In an effort to reduce water scarcity risk for users, these organizations employ various investment strategies, including increasing water storage capacity, improving conveyance infrastructure, and purchasing additional water rights. Although previous studies have focused on farm-level adaptations, very little is known about the investment decisions made by IOs in the adoption of adaptation strategies; this literature gap represents an urgent and understudied element in drought adaptation, especially as delays in off-farm action may compound long-term vulnerability to drought. This study empirically evaluates IO long-run adaptations to water scarcity in the Western region. Specifically, we explore differences in IO adaptation investments based on their past experiences of water scarcity and their organizational characteristics. This analysis leverages novel micro-level data from the Survey of Irrigation Organizations (SIO), along with county-level climate data from the U.S. Drought Monitor. We find evidence indicating that while water scarcity experience is a driver of some adaptations, other characteristics display a higher association with adaptation likelihood. We uncover a non-linear relationship between organization size and adaptation likelihood, and present evidence indicating a positive relationship between eligibility for federal support

programs and adaptation investments. This study provides vital insights into the factors that may motivate organization- level efforts to ensure the resilience of irrigated agriculture, and may inform new pathways to promoting necessary adaptation decisions.

## 2. INTRODUCTION

Global population growth, increasingly severe climate change impacts, and unsustainable farming practices jointly spur growing concerns regarding the ability of our food system to feed the world (Dinar, et al., 2019; Zilberman, et al., 2018; Molden, 2007). Historically, the development of irrigation has played a key role in increasing agricultural productivity, but its viability and effectiveness are threatened by growing water shortages (Musselman, K., et al, 2021). Freshwater availability is the leading constraint in agricultural production, and many areas of the world are experiencing increasingly frequency drought periods (Hanjra and Qureshi, 2010; Chiang, et al., 2021; Mancosu, et al., 2015). In the U.S., irrigated agriculture accounts for approximately 54% of the total value of U.S. crop sales, while only making up 17% of farmland (Hrozencik, et. al., 2023; USDA-ERS, 2022). This paper focuses on the Western U.S., which accounts for nearly three quarters of irrigated land in the U.S. (Schaible and Aillery, 2012). The region has been experiencing severe droughts for the last 20 years (Hrozencik, 2023), and these multi-year droughts have been significantly limiting the amount of water available to all sectors, most substantially the agricultural sector. Adapting irrigation systems to increasing water shortages through water conservation practices is crucial to ensure resilience in agricultural production (Earnhart and Hendricks, 2023; Olmstead, 2010). These adaptations can be implemented at the farm level, the institutional level, or the government level through different mechanisms. This paper examines off-farm adaptations to water scarcity in the Western US. These adaptations are typically implemented by irrigation organizations, and often entail substantial upgrades to infrastructure that was initially designed to operate under less severe climate conditions. We empirically analyze the influence of water scarcity experience and organizational characteristics on an irrigation organization's decision to invest in water scarcity adaptations.

Irrigation organizations (IOs) are defined as operations which manage the delivery of water from source to consumer — including domestic, commercial, and agricultural users — and in some regions, most notably in the High Plains Aquifer region, play a role in managing on-farm groundwater usage (Potter, et al., 2023). The membership of these IOs is comprised of its water users or customers. The Western U.S. provides an optimal environment for studying IO adaptations to water scarcity due to the heavy reliance on surface water deliveries in the region, and the critical role that IOs play in delivering this water. Approximately 42% of freshwater usage in the U.S. goes towards irrigated agriculture (Hrozencik, 2023), and in the Western U.S., over 80% of surface water withdrawals are managed by IOs (Potter, et. al., 2023). In 2018, IOs delivered approximately 67 million acre-feet (over 21 trillion gallons) of water, and of those, approximately 41 million acre-feet (14 trillion gallons) went to farms and ranches (Potter, et. al., 2023). In 2018, these entities served 55.5% of the total irrigated acres in the West (USDA-NASS, 2019). In an effort to reduce water scarcity risk for users, these organizations employ various investment strategies, including increasing water storage capacity, improving conveyance infrastructure, and purchasing additional water rights (Hrozencik, et. al., 2021; Bretsen and Hill, 2006; Libecap, 2011). Although these adaptations are largely necessary for continued success in agricultural production in the

Western U.S., they are relatively under-adopted. This is due largely to their prohibitively high costs (Hrozencik, et al., 2021). This barrier has been somewhat mitigated by government intervention, through mechanisms such as subsidizing or incentivizing adaptation. However, it is unclear whether this level of policy intervention is necessary to induce water scarcity adaptations on the institutional level, or if increasing water scarcity alone is a powerful enough signal to induce effective long-term responses.

In this study, we analyze the factors that influence the likelihood of an irrigation organization (henceforth referred to as an "IO") to invest in water conservation adaptations. We focus specifically on two key adaptations: lining canals or replacing them with pipelines, and installing technology to measure the flow rate and volume of water. Accurate water measurement, or 'water accounting', is a critical component in drought planning and projecting water demand, as well as enforcing adherence to water allowances (Turner, et al., 2011). Conveyance losses present a direct limitation to meeting the water demands of irrigators under drought conditions. These losses of water from an irrigation system occur due to seepage of canals leaking pipelines, and evapotranspiration. Across the US, IOs reported conveyance losses of over 15 percent (USDA-NASS, 2020). Improving the conveyance efficiency of canals through lining or piping is similarly crucial in maximizing the volume of water that reaches an irrigated farm, and for mitigating water shortages during drought periods. IOs play a critical role in determining how droughts translate to farm-level outcomes. Their investment decisions are a key driver of agricultural drought resilience. As groundwater aquifers continue to deplete, and the frequency of surface water shortages continues to increase –

both in the Western US and globally – there is an urgent need for the implementation of effective adaptation strategies at the institutional (off-farm) level. Without adaptation, IO members will likely be unable to sustain the productivity of irrigated agriculture in the face of increasingly frequent and severe droughts.

The factors that contribute to the adaptation investment decisions of IOs is unclear, but understanding what motivates these organizations is key to developing effective water scarcity adaptation strategies. Our empirical analysis leverages novel micro-level data from the 2019 Survey of Irrigation Organizations (SIO), the first large-scale data collection effort aimed at IOs in the Western US since 1978 (USDA-NASS, 2019), to investigate the role that various key institutional characteristics have in determining the likelihood that an IO will adopt an adaptation strategy, as well as their sensitivity to water shortages. This study examines whether IOs are motivated to adopt water-saving adaptations through natural factors, or if policy intervention is needed. We use a piecewise logistic regression to estimate the impacts of these key characteristics and past water scarcity experience on an IO's likelihood of investing in any water scarcity adaptation, measurement infrastructure, and canal lining or piping.

The estimations presented in this study highlight the impacts of organization size, presence of federal assistance, and water scarcity experience on an IO's adaptation outcome. We find evidence indicating that although IOs that experience short-term water scarcity are more likely to invest in water scarcity adaptations, particularly conveyance improvements, other organizational characteristics may be more influential. Organizations that receive water from a federal source, indicating eligibility for government subsidies, are far more likely to adapt. This signals that although water scarcity experience is a motivator for some adaptations, policy intervention may be necessary for others. Further, our results uncover a nonlinear relationship between IO size and adaptation likelihood. Although the marginal effects of size are significant and positive for all IOs, smaller organizations experience a stronger response to increased size than larger organizations, particularly for likelihood of investments in conveyance improvements.

Our key findings suggest that access to federal support significantly drives IO investments in water scarcity adaptations, suggesting that policy incentives are an effective and valuable tool to mitigate the impacts of water scarcity in the agricultural sector. This also exemplifies the need for IO decision-makers and teams to prioritize seeking external funding sources for, and particularly for IOs with significant political power, the value of advocating for expanded funding opportunities. This association is particularly applicable for adaptations in other countries; centralized funding sources may be crucial for building agricultural resilience to growing water scarcity. In this context, the nonlinear impacts of IO size suggest that policy incentives geared specifically towards adaptation could be beneficial, as propelling these organizations above a certain financial threshold may yield large gains.

This study contributes to the small but growing body of literature surrounding IO-level adaptations in the Western U.S. While Previous literature has examined farm-level adaptations in the Western U.S. (Manning, et al., 2018; Mukherjee and Schwabe, 2015; Burke and Emerick, 2016; Brent, 2017), and institution-level adaptations in other countries (Hao, Quian, and Li, X., 2016; Muller, Muller-Itten and Gorelick, 2017; Manjunatha et al., 2011; Zheng, et al., 2011), very little is known about the institutional adaptation practices in the Western U.S. Gaining an understanding of factors that may influence off-farm adaptations to drought is critical to maintaining future agricultural productivity.

## 3. BACKGROUND AND INSTITUTIONAL CONTEXT

Irrigation Organizations (IOs) in the Western US are diverse in structure, member composition, reach, and power, both political and financial. We must couch our efforts to understand the drivers of IO decision making within a larger discussion of these facets, particularly as the richness of literature surrounding these organizations falls within these areas.

### *3.1 The Development of Irrigation Organizations in the Western US*

The history and status of water policy in the Western U.S. provides crucial context for the evaluation of IO adaptations. As migrants flooded to the Western U.S. in the early to mid-1800's, it quickly became clear that the standing riparian water doctrine – which allows landowners whose property borders surface water sources to use as much water as they want – would not translate to these arid and semi-arid regions (Leonard and Libecap, 2019). Water from streams and rivers would have to be transported to the parcels that were suitable for agricultural production, and this water was scarce. Unlike in the Eastern U.S., the geographical characteristics of the West divorced riparian land ownership from water rights (Edwards, Sanchez, and Sekhri, 2023). Therefore, the "first come first serve" ideology was adopted for water use and was signed into law as the prior appropriations doctrine.

With uncertainty about future water supply, there was little incentive for individual producers to invest in water conveyance infrastructure (Edwards and Smith, 2018). Essentially, farmers were reluctant to establish plots that relied on irrigation knowing that other producers could divert water upstream, leaving them with insufficient water. However, the prior appropriations doctrine allowed the earlier rights holders more certainty about their future water supply. Although under this policy the question of continued water access was answered – at least for those with senior water rights – the massive capital investments and technical expertise that was needed to build large ditches was largely inaccessible to irrigators (Coman, 1911). Irrigators came together to pool their resources for these large projects. This gave rise to a multitude of IO types, each with their own shortcomings. For-profit land development companies and irrigation companies would construct (often shoddily) conveyance infrastructure and sell prospective farmers the promise of productive lands. These models largely failed. Ultimately, culpability for these failures can be attributed to the opportunism of both farmers and water companies, each holding power to "extort" the other by refusing to purchase or deliver water, respectively. However, this dynamic was largely overcome by a form of vertical integration, where the users of water were also responsible for its delivery. IOs with a cooperative structure, known as mutual IOs, rose to prominence, where its shareholders were the water users themselves. Mutual IOs suffered from lack enforcement power, with little opportunity for recourse if users did not pay, as well as hold-out problems (Hanneman, 2014).

With small ditches, there was little need for collaboration. However, with larger conveyance distances and longer canals, the scale of necessary investment was vastly larger. Irrigators began joining their investments to make large constructions possible at smaller upfront costs (Leonard and Libecap, 2019; Bretsen and Hill, 2007; Hanneman, 2014). This gave rise to the aforementioned mutual IO's, classified as unincorporated and incorporated mutuals with distinct levels of formality. Leonard and Libecap (2019) find that the benefits of these mutual agreements rose as the number of participants increased. Proportionally, the larger the group, the more robust the infrastructure was. This trend is evidence of the economy of scale, which enabled IOs to make these otherwise prohibitively expensive investments. Irrigation districts also came into prominence during the late 1800s, often replacing mutuals or companies, which were formed through bottom-up farmer action. Irrigation districts are local government entities that have substantial political power including eminent domain and bond issuance (Bretsen and Hill, 2007).

While early investments by water users are responsible for much of the canal infrastructure still present in the Western US, public investment is largely responsible for the core platform upon which these systems rely. The U.S. Bureau of Reclamation, installed as a federal agency by the Reclamation Act of 1902, along with the U.S. Army Corps of Engineers and various State agencies facilitated the development of many canals and dams on which IOs rely (Swain, 1970; Reisner, 1993). Reclamation projects include the Hoover dam and the Central Valley Project, and represent a mass funneling of public funds towards water infrastructure development concentrated in the early to mid-1900s. These investments largely enabled the success of IOs as we know them today.

Ultimately, the most prominent avenue for the development of irrigation infrastructure in the Western US was through joint investments and decisions by water users. Investments from these joined groups of irrigators with aligning interests are responsible for the vast majority of irrigation infrastructure in the Western US, although largely underpinned by federal dams and region-wide infrastructure. Therefore, the existence of irrigation infrastructure in the region is evidence of successful collective action, and this legacy continues to underscore the water management systems in the West today. This historical success of these IOs now faces an unprecedented challenge: the infrastructure made possible through collective action now urgently requires substantial upgrades to operate under increasingly severe drought conditions. Without these investments, IOs will increasingly fail to deliver sufficient water to their members in times of drought, which will threaten the long-term success of irrigated agriculture in the Western US.

### *3.2 Irrigation Organization Structures and Operation*

We consider IOs as entities that manage the delivery of water to farms and ranches. A mere 14% of IOs deliver water to non-agricultural users, and only 3% provide water for electricity uses. However, some IOs are solely involved in groundwater management (Wallander, et al., 2022). **Table 1** provides a brief overview of the four key types of IOs that we consider in this study. We generalize that IOs are typically user owned or

**Table 1. Irrigation Organization Types**

| IO Type | Description | Legal Status/ Formation | Powers | Revenue |
|---|---|---|---|---|
| **Unincorporated Mutual** | Small and informal groups of ditch users, voluntary agreement to manage an irrigation system | Not a legal entity, but some are legally recognized | Limited powers; some states grant eminent domain | Member contributions |
| **Incorporated Mutual** | Shareholder-owned nonprofit: Farmers hold shares proportional to their water rights; delivery based on shares | Non-profit corporation, often governed by a board of directors | Can contract, own property, some states grant eminent domain | Sale of shares, water delivery fees. Typically, a non-profit. |
| **USBIA Project** | BIA administration, collaboration with local tribal governance or other IOs | Federal project, thus operate under federal regulations | Federal enforcement powers | Federal appropriations, fees to water users |
| **Irrigation District** | Public Corporation: Local government unit to develop/manage irrigation infrastructure | Formed by landowner petition; voting may be based on land ownership | Power to tax, issue bonds, eminent domain, enforcement of water allocations | Property taxes, issuing bonds for projects, water delivery fees |

*Sources: Bretsen and Hill (2007); Libecap, 2011; Hanneman, 2014; USDA-NASS, 2020.*

operated. The USDA Survey of Irrigation Organizations (SIO) finds that the majority of IOs in the U.S. are incorporated mutuals, followed by irrigation districts. Across the U.S., unincorporated mutuals incorporated mutuals, irrigation districts, USBIA Projects, and "Other" types serve an average of 20, 51, 168, 357, and 121 farms, respectively (USDA-NASS, 2020). Most IOs are governed in some way by the water users directly, especially in less formal types, or by a board of directors, which is either elected or appointed by water users (Bretsen and Hill, 2007). This user-controlled governance structure is intended to ensure the IO operates on behalf of the water user's collective interests; votes made by water users are often weighted by land ownership, intended to reflect the nature of appropriative water rights (Hanneman, 2014). However, critics of IO governance argue that their very structure tends to favor the interests of the wealthiest or largest landowners: they may be undemocratic by design (Owen, 2024). In the face of growing water shortages and a need for adaptation, this may be a barrier for such action, especially by risk-averse water users.

The membership composition of IOs varies in addition to governance and power. IO members are typically farmers or ranchers, though some IOs also serve cities or municipalities, power plants, industrial projects, or recreational projects. All parties are impacted by water scarcity risks, though we focus on farmers. We consider the IO as a collective of users whose total objective is to meet the water demands of its users and to mitigate the risks associated with annual variability in water supply. IO members typically hold shares of the IOs water rights, and delivery is based on these shares. This cooperative structure allows IOs to pool member resources and make joint operational decisions as a coordinated unit. Understanding this cooperative structure is key for evaluating the larger IO decision-making process.

### *3.3 Irrigation Organizations and Adaptations to Water Scarcity*

IOs adapt to water scarcity through a variety of methods in an effort to reduce the drought-induced losses incurred by their members. These methods include upgrading physical infrastructure, expanding water rights portfolios, compensating voluntary land fallowing, and offering cost-share programs to farmers who wish to adapt at the farm level (source). The most common conservation investment made by IOs is flow rate metering (39% of IOs), followed by canal lining or piping (32% of IOs) (Wallander, et al., 2022).

Although the wide-spread adoption of these adaptations would likely prove invaluable in establishing drought resilience, the relatively low level of adoption indicates that these practices have significant barriers, the primary being significant cost. Hrozencik, Potter, and Wallander (2023) cite estimates of canal improvement costs from various sources, indicating that lining a small canal ranges from $30,000 and $228,000 per mile. The authors reference the All-American canal to demonstrate the costs of lining a large canal, reporting a cost exceeding $1.8 million per quarter mile. Finally, replacing a canal with piping costs between $0.6 and $3.2 million per mile. These examples help to illustrate the prohibitive expense of conveyance improvements. **Table 2** adds to this description, providing further examples of investment costs, along with investment descriptions, sourced from the WaterSMART data portal.

**Table 2. Irrigation Organization Water Scarcity Adaptations**

| Adaptation Type | Description | Cost Examples (WaterSMART) | Prevalence |
|---|---|---|---|
| **Flow Rate Measurement** | Measurement technology at headgates, turnouts, or throughout the conveyance infrastructure | Lower Tule River Irrigation District: $6,396 per flow rate meter installation | 39% of IOs |
| **Canal Lining/Piping** | Improving conveyance efficiency by reducing leaks/evaporation | Bard Water District: $968,680 per ½ mile of lining<br><br>Moore Lake WUA: $320,255 per mile of piping | 32% of IOs |
| **"Other"** | Fallowing compensation, Cost-Share Programs, Diversion/regulating reservoirs, other | Dungeness Off-Channel Reservoir: $31 million for 1,600 ac. ft. reservoir<br><br>Imperial Irrigation District: $300/ac. ft. for farmers not to irrigate | Reservoirs: 11%<br>Cost-Share: 8%<br>"Other": 7%<br>Fallowing: 1% |
| **Any Adaptation** | All listed above | — | — |

*Source: WaterSMART Data Portal, Accessed March, 2025.*
*Internet Site: https://www.usbr.gov/watersmart/*
*Interactive Data Portal:*
*https://experience.arcgis.com/experience/bf5c5357e7044e0c80d5a55788d1db34*

While we highlight the importance of these infrastructure adaptations in improving drought resilience, previous literature suggests that on-farm improvements to irrigation technology may actually increase water use by encouraging the expansion or intensification of irrigation, particularly without preventative governance mechanisms (Pfeiffer and Lin, 2014; Grafton, et al., 2018).

Today, state and federal programs play a key role in facilitating the implementation of these adaptation practices at both farm and IO levels. They provide external funding assistance and technical assistance to directly support these vital investments. Key programs managed by the USDA, namely the Environmental Quality and Incentives Program (EQIP) and the Conservation Stewardship Program (CSP), have been instrumental in supporting on-farm adaptations. However, previous research indicates that farmer participation in these programs is driven by past water scarcity experience rather than preventative motivations (Wallander, et al., 2013). The 2018 Farm Bill expanded eligibility for EQIP funding to include IOs, allowing them to apply for assistance for large-scale infrastructure projects (NSAC, 2019; US Congress, 2018). Further federal programs include the US Bureau of Reclamation WaterSMART program, as described above, and the Farm Service Agency Conservation Reserve and Enhancement Program (CREP). The CREP combines federal and non-federal funding sources to target regional- or state-specific conservation issues, compensating farmers for voluntary land retirement (USDA-FSA, 2025). Recent state-level policies have impacted groundwater management approaches, enabling or mandating the establishment of groundwater management organizations (e.g. Kansas' Groundwater Management

Districts, Nebraska's Natural Resource Districts, California's Groundwater Sustainability Agencies) (USDA-FSA; Nebraska Association of Resource Districts; California Department of Water Resources). These government programs offer external funding opportunities and implementation assistance, highlighting the continued importance of policy measures to overcome adaptation barriers.

# 4. LITERATURE REVIEW

## *4.1 Agricultural Adaptation to Water Scarcity in the Western U.S. Farm-Level Adaptations and Implications*

Various studies have examined how farmers are adapting to climate change and variability in water supply. Farm-level adaptations include strategic crop choices, technology improvements, land fallowing, and diversification of water rights portfolios (Coburn, et al., 2022; Li, et al., 2022; Mukherjee and Schwabe, 2015; Haggerty, 2021). Findings regarding on-farm adaptations suggest that farmer's cropping decisions, and resulting profits, are strongly influenced by their expectations of water scarcity; the expansion of basin-level water storage, and its resulting added water security, may increase farmer profits by allowing space for optimized cropping decisions (Manning, et al., 2017). These farm-level adaptations represent crucial mechanisms for addressing agricultural outcomes of water scarcity.

Though the effectiveness of on-farm adaptations is well established, farmer's actual capacity or willingness to implement these strategies varies significantly. Research indicates that long-run adaptation strategies may not be more effective than short-term measures, which may be due to limited available adaptation opportunities or prohibitively high costs (Burke and Emerick, 2016). Further, though farmers adapt across various margins such as improving irrigation methods and optimizing cropping choices, their chosen adaptation strategies may not meaningfully mitigate drought-induced losses (Hagerty, 2022).

Under the system of prior appropriations, securing future water access is a key component in ensuring sustained agricultural productivity during drought periods. By diversifying water rights portfolios, farmers are able to achieve flexibility in their water use, shielding farmers from the risks of water scarcity (Mukherjee and Schwabe, 2015). Further research investigates the ways in which real water scarcity risks influence farmer's irrigation decisions, exploiting heterogeneity in water rights between irrigators; findings suggest that under higher water risk, junior water rights holders that rely primarily on surface water for irrigation are most likely to reduce their irrigated acreage, whereas those who have groundwater access instead substitute irrigation water sources (Li, et al., 2019). Similarly, evidence indicates that between areas with and without groundwater access, farmers without access adapt to less certainty by planting more drought-resistant crops, though there is no significant difference in drought resilience outcomes between the two groups (Hornbeck and Keskin, 2014). Individual farmers, specifically those with junior water rights, may adapt to water scarcity by fallowing land (Coburn, et al., 2022). Importantly, not all water rights are similarly valuable to farmers (Brent, 2017). The results of these previous studies suggest that individual and basin-level adaptations can help to mitigate the negative impacts of water scarcity, though benefits may not be evenly distributed. The anticipation of future water scarcity and farmer's confidence in water security drives investment adaptations on the farm level.

Farm-level perceptions of water scarcity risk is a key factor in determining behavioral outcomes. Research suggests that irrigator's expectations of water availability impact their planting decisions, thus increasing profits; improving water storage infrastructure may also increase profits (Manning, et al., 2017). This implies that the ways in which climate change impacts translate to agricultural outcomes is highly dependent upon adaptation responses. Further research investigates the ways in which top-down water management decisions and water scarcity adaptations influence farm-level outcomes. Further evidence suggests that in response to policy-imposed water restrictions, farmers were more likely to reduce the intensity of water applications rather than fallow their cropland (Drysdale and Hendricks, 2018; Deines, 2019).

Some research has investigated the ways in which being a member of an IO influences on-farm adaptation decisions. This approach introduces an interesting perspective regarding the substitutability between on-farm and off-farm adaptations. Farmers with access to more secure surface water sources are less likely to invest in on-farm adaptations (Olen, et al., 2015). Previous research indicates that IO membership proves beneficial to individual farmers (Ji and Coburn, 2018; Mukerjee and Schwabe, 2015).

### *4.2 Irrigation Organization Decisions and Behavior Collective Action*

The conceptual bases for our study – common pool resources, the tragedy of the commons, and collective action – have been discussed at length throughout the 20th and

21st centuries in economic literature. Water is a common-pool resource, and its users are motivated to overconsume it because they do not incur the external cost of other user's experiences of water shortage (Edwards, Sanchez, and Sekhri, 2023). Hardin first introduced the tragedy of the commons concept in 1968 (Hardin, 1968), and self-governance as a means to address the management of common-pool resources has been examined at length (Smith, et. al, 2015; Perez-Quesada and Hendricks, 2021; Smith, et. al. 2017). Historically, the existence of IOs themselves is evidence of effective collective action in addressing surface water management, as their development resulted from a coordinated investment by individual farmers (Leonard and Libecap, 2019). Therefore, this study posits that all IO decisions exist within the broader framework of collective action, and we hypothesize heterogeneity will be observed not between those who engage in collective action and those who do not, but between various levels of collective action within organizational decision making.

Collective action as a means to address the governance of common-pool resources, specifically groundwater, has been deemed an effective strategy in numerous studies (Smith, 2015; Libecap, 2011; Bruns, 2023). Specifically in the context of groundwater management, there have been recent case studies examining the effectiveness of collective action in protecting these particular commons, both domestically and abroad (Edwards, 2021; Ayres, 2019; Michler, 2020; Smith, 2017; Hornbeck, 2014). Ostrom (2002) argues that in a commons where the resource is abundant but becomes scarce, self-organization is likely. She proposes eight tenants of sustainable self-governing organizations, which include collective-choice arrangements, whereby the members of an organization may have input in determining rules, monitoring, where users are held accountable, and (for resources that are part of larger systems) nested enterprises, where governance is organized within multiple layers. This theory of self-governance has been evaluated by Perez-Quesada and Hendricks (2021), in the context of groundwater management in Kansas. They conclude that small-scale collective action in this context is possible, but the larger the geographical area becomes, the less likely users are to participate in groundwater management planning.

Historically, the establishment of IOs in the Western US is evidence of effective collective action. Establishing comprehensive irrigation infrastructure in the region faced many barriers, including the high transaction costs of coordinating efforts, unclear property rights, and geographically sparse water access (Coman, 1911; Libecap, 2011). The physical characteristics and legal complications of surface water resulted in free-rider problems, holdout problems, and an uncertain distribution of cost-benefit outcomes (Libecap, 2019; Libecap, 2011; Bretsen and Hill, 2007). As discussed above, these problems were overcome through the establishment of clear property rights through the prior appropriations doctrine, the pooling of water user's resources through early IO formation, and legal enforcement mechanisms. Today, many of the original problems faced have evolved. As the frequency of water scarce periods increases, the need for collective action lies in climate change adaptation. Collective action barriers are largely the same, though repackaged in the context of modern problems. Now, IOs must expand their reach beyond water allocation to address the need for water conservation. Mirroring the initial presentation of the free rider problem in IOs, users today may resist adaptation investments if their direct benefits are not clear (Libecap, 2011). Literature detailing the historical establishment of IOs offers key insights to the future of collective action.

### *4.3 Organization-Level Adaptations*

Although previous studies have focused on farm-level adaptations and the effectiveness of collective action as a means to address the depletion of the groundwater commons, very little is known about the investment decisions made by IOs in the adoption of adaptation strategies. Previous studies that examine collective action in institutional water management have often focused on developing countries, or other developed countries with similar IO systems (Hao, C. J., Quian, H., and Li, X., 2016; Muller, M.F., Muller-Itten, M.C., and Gorelick, S. M., 2017; Manjunatha, A. V., et al., 2011; Zheng, H., et al., 2011). The IOs in developing countries (commonly called Water User Associations of WUAs) are typically much smaller than those in the US, and more closely resemble "unincorporated mutual" IOs, or the early formation of our modern forms. Globally, water rights markets and "water banking" are considered effective adaptation strategies (Edwards, Sanchez, and Sekhri, 2023). Irrigation institutions in Australia's Murray-Darling Basin have had significant success in adapting to drought conditions through investing in off-farm and on-farm infrastructure improvements and participating in a robust water rights trading market (Grafton and Wheeler, 2018; Wheeler, et al., 2014). Though there is a limited water rights market in the Western U.S., it is vastly underdeveloped. The Australian "cap and trade" water rights system is very robust, allowing IOs to adapt largely through enabling effective market mechanisms. Further evidence indicates that in Spain, where physical infrastructure is limited, successful adaptation has been enabled through a combination of infrastructure improvements and water trading (Garrido and Calatrava, 2010). However, the development of effective water markets in the U.S. is hampered by “institutional path dependence” the historical development of IOs in the region was directed by stable water supply and strict property rights definitions. Changes to the fundamental structures of IOs, such as enabling participation in water markets, is impeded by high transaction costs and bureaucratic friction (Libecap, 2011). Further key research on IOs around the world highlights that the effectiveness of IO structures is highly dependent on local context; between market-based systems, collectives, and state institutions, there is no “winner.” Rather, different levels and forms of governance are most effective when they interact with one another (Meinzen-Dick, 2007).

In the Western U.S., many studies that examine collective action in groundwater management are case studies, rather than using observed data, as we are doing here. Cody (2015) evaluates the effectiveness of self-governance in the management of the groundwater commons in Colorado’s San Luis Valley, presenting findings that indicate external social shocks are the strongest drivers of collective action, while drought shocks have had the most influence on governance adaptations. Again, focusing on the San Luis Valley, Smith (2017) found that locally implemented price interventions (groundwater taxes) to encourage irrigators to decrease water use successfully decreased groundwater extraction rates. Drysdale and Hendricks (2018) found evidence that Kansas irrigators responded to local groundwater restrictions by reducing water use intensity and cropping patterns. . Leonard and Libecap (2019) present evidence indicating that the establishment of the prior appropriations doctrine in the Western US was crucial in overcoming collective action problems, enabling the development of IOs.

In the context of IOs as a whole, it is evident that farmers derive economic benefits from being a part of these organizations (Ji and Coburn, 2018). Zema (2020) found evidence that factors including organization size and higher number of customers leads to the sustainability of water user associations (Zema, D. M., et. al, 2020). Libecap (2015) discusses the growing opportunity costs of a rigid water market system, and concludes that any disruption from the "institutional path dependence" observed in irrigation institutions would only arise with the backing of the stakeholders, including the members of IO boards and water users. Although Libecap is referencing the water markets systems, this idea can be extended to any institutional decisions that would appear to favor any outside water users, including downstream farmers, municipal water users, and even non-market environmental beneficiaries. Therefore, it is important to investigate what factors contribute to the adoption of water conservation adaptations, which benefit not only irrigators within an IO, but all water users.

# 5. CONCEPTUAL FRAMEWORK

## *5.1 Investment Decision Framework*

To motivate and inform the empirical model of irrigation organizations' (IOs) infrastructure investment decisions, the conceptual framework posits that these decisions are primarily driven by changes in water availability and the need to improve delivery efficiency. IOs operate as collective entities composed of members—such as farmers, municipalities, and power plants—who pool resources to manage water deliveries.

Members typically hold shares that entitle them to a portion of the distributed water. The primary objective of IOs is to meet their members' water demands while mitigating risks associated with supply variability. The existence of these IOs is a given, but the methods they employ to achieve their objective of delivering water in the face of climate change is the subject of this decision-making process.

To deliver water to users, IOs own and operate conveyance infrastructure, where water losses can occur during transport. Monitoring water use throughout the conveyance system is also challenging, as not all diversion points and users are metered. Since water delivery is determined by the organization's water rights—where junior rights are curtailed first during shortages—investments in infrastructure improvements and monitoring become increasingly valuable as scarcity intensifies (Libecap, 2011). In the face of increasing water shortages, the IO confronts two options: delivering less water during the times of drought or investing in infrastructure improvements that may offer resilience to future water shortages. Consequently, each IO decides whether to invest in conservation practices, such as upgrading conveyance infrastructure or installing measurement systems, if the total net benefits of its members are positive and exceed those in the baseline scenario (no investment) (Ostrom, 2002). This decision is conditional on past experience of water scarcity, government incentives and organizational characteristics:

$$NB_i^j = \sum_k B_k^j(\varphi_i, ws_i, \rho_k) - C_k^j(\varphi_i, \theta_i, \rho_k) > 0$$

where $NB_i^j(.)$ is the total net benefit of investing for IO $i$ relative to the baseline scenario of no investment, $B_k^j(.)$ represents benefits of investing in practice $j$ for member $k$, as a function of organizational characteristics, $\varphi_i$, IO's past experience of water scarcity, $ws_i$, and members characteristics, $\rho_k$. $C_k^j(.)$ reflects costs of investing in practice $j$ as a function of organizational characteristics, $\varphi_i$, government financial incentives, $\theta_i$, and members characteristics, $\rho_k$. j is any conservation practice.

The framework generates two propositions based on how water scarcity and financial incentives affect investment decisions:

$$\text{Proposition 1: If } \frac{\partial B_{kj}(\varphi_i, ws_i, \rho_k)}{\partial ws_i} > 0 \text{ or } \frac{\partial C_{kj}(\varphi_i, \theta_i, \rho_k)}{\partial \theta_i} < 0, \text{ then } NB_i^j > 0.$$

The IO is more likely to invest in measure $j$ if water becomes scarcer or if part of the cost of investment is subsidized.

Empirically, the IO investment decision can be modeled using a random utility framework (McFadden, D., 1972; Train, K. E.; 2009), which compares the net benefits of investing in water conservation practice $j$ ($NB_i^j$) and an alternative conservation practice $j'$ ($NB_i^{j'}$). The benefits associated with a given decision $j$ can be decomposed into an observable component $V_i^j$ and an unobservable component $\varepsilon_i^j$,

$$NB_i^j = V_i^j + \varepsilon_i^j = \alpha_j + \beta_j \varphi_i + \gamma_j \, ws_i + \delta_j \, \theta_i + \varepsilon_i^j$$

where $\varphi_i$ is a vector of IO characteristics, $ws_i$ reflects past experience of water scarcity, and $\theta_i$ represents government incentives. Assuming that an IO, $i$, invests in conservation practice $j$ if the total net benefits of its members ($NB_i^j$) exceed those of investing in $j'$ ($NB_i^{j'}$), the probability of investing in practice $j$ can be defined as:

$$\Pr(Invest_i) = \Pr\left(NB_i^j > NB_i^{j'}\right)$$

$$= \Pr\,(NB_i^j + \varepsilon_i^j > NB_i^{j'} + \varepsilon_i^{j'})$$

The unobservable component is IID and follows the Type I extreme value distribution. Thus, the probability of investing in water conservation practice $j$ can be expressed as:

$$\Pr(Invest_i/V_i) = \Gamma(V_i) = \frac{\exp\,(V_i)}{1 + \exp\,(V_i)},$$

Where $\Gamma(.)$ represents the logistic cumulative distribution function, which ensures that the probability lies between 0 and 1.

### *5.2 The Role of Water Scarcity, Government Incentives, and Organizational Characteristics in Shaping Investment Decisions*

***Resource Scarcity***

The degree of water shortage that is felt by the users of an IO serves as a key signal for investment likelihood. If the water resource is already exhausted, then users will have no incentive to invest in water conservation adaptations. However, if the users observe some increasing level water scarcity, they will have a greater incentive to invest (Ostrom, 2002; Perez-Quesada and Hendricks, 2021). The cost of non-adoption will increase as drought events become more frequent and severe. We expect that greater water scarcity may increase an organization's expected returns on an investment, thus increasing investment likelihood. Because we are investigating investments made within the five years prior to the SIO being collected, we assume that the drought-induced need to adapt that is captured in our data is spurred primarily by drought events during the same short-term time frame. Further, we expect IOs to have varying adaptation responses based upon their access to groundwater. Farm-level adaptations vary based on groundwater access, as this mitigates the costs of non-adoption in drought events (Li, et al., 2019; Hornbeck and Keskin, 2014). We expand this to motivate our expectation of IO behavior; IOs with groundwater access may be less likely to invest in surface water adaptations, as there is a substitution effect between surface water and groundwater. Previous literature supports our expectation that water scarcity experience heightens the perceived benefits of investing in water scarcity adaptations (Manning, et al., 2018).

***Organizational and Infrastructure Characteristics***

The existing infrastructure of an IO, as well as its institutional structure and financial capabilities, influence its ability and willingness to make water conservation investments. In this study, we use the number of farms or ranches that an organization has the capacity to serve as our primary representative measure of financial capability. We make the assumption that a higher number of farms (i.e. customers) is positively correlated with a larger revenue stream, thus providing the organization more funding with which to make infrastructure investments. This prediction echoes the findings of Leonard and Libecap (2019); the results of the study indicated that in the early development of irrigation infrastructure, organization size was associated with size of diversion infrastructure, likely as a result of returns to scale under high fixed costs. We expect to observe a similar relationship between organization size and likelihood of investing in water conservation adaptations.

We expect that the governance structure of an organization is a key determinant of investment likelihood, as it dictates the means by why an organization engages with the decision-making process. This model includes two representative measures of governance structure: an organization's degree of formality and whether water users can vote on key decisions. We predict that more formal organizations have a higher likelihood of investment, due to their heightened power and established procedures. These more formal IOs are also often linked with federal water sources, particularly irrigation districts, which may further influence adaptation. In line with our theoretical framework, we predict that those that allow users to vote on key decisions, including investment decisions, will be more likely to invest, as we assume stakeholders who are directly impacted by drought will want to mitigate its negative consequences. However, previous literature highlights the issue of "institutional path dependence" as a barrier for IOs — particularly those which are long-established — to engaging in water markets or investing in on-farm adaptations: because IO members may be uncertain about how the costs and benefits of these changes would be distributed, key stakeholders may display strong resistance to such changes (Libecap, 2011; Cody, et al., 2015).

The existing infrastructure that an IO either manages or operates within influences investment decisions as well, and we expect to observe heterogeneous impacts between types of investment depending on their existing operational infrastructure and user needs. If an IO owns a reservoir, we generally expect them to have greater financial capacity compared to non-owners, and thus, we expect that these organizations will have a higher adaptation likelihood overall (Manning, et al., 2018). Although this model does not directly control for miles of conveyance infrastructure that is managed by an IO, we assume that the number of farms that an organization can serve is linked with managing more canal or ditch miles, particularly for organizations that primarily deliver surface water. Thus, we expect the effect of organization size to be especially pronounced for investments in canal lining or piping.

***<u>Government Incentives and Policies</u>***

Although the development of the prior appropriations doctrine helped to encourage collective action for the development of water infrastructure in the western US, these pre-existing problems may be resurfacing as water availability diminishes. Because of the nature of surface water resources, the benefits of investments in water conservation adaptations spread beyond the bounds of the organization that makes the investment. This may induce the perception of a free-rider problem between organizations. For example, if an upstream organization is facing the decision to invest, they may be disincentivized if they believe their investment will dissuade a downstream organization from investing. They may perceive non-contributing users benefiting from a high-cost investment as undeserved, and may underinvest as a result. This type of market failure can be mitigated by government intervention, such as subsidies or cost-share programs, or policy incentives that encourage water conservation. The model seeks to capture this effect by controlling for the source of the water that an IO manages. We first predict that if an IO receives water from a federal source, we will observe a greater likelihood of investing in a water conservation adaptation. This is due to initiatives such as the "WaterSmart" program, that provide funding for these measures explicitly for organizations who receive water from a U.S. Bureau of Reclamation source. Because funding is likely the most substantial barrier to adaptation, the ability to participate in programs that subsidize these costly measures may be a major determinant of implementation.

## 6. DATA AND METHODS

### *6.1 Data*

#### ***2019 Survey of Irrigation Organizations***

This study empirically evaluates which factors may influence the adaptation likelihood of surface water IOs in the Western U.S. Given the present and future acceleration of drought-induced consequences for the agricultural sector, the risk of inaction by IOs is significant. We use data from the Survey of Irrigation Organizations (SIO), collected in 2019 by the USDA-ERS. The SIO collected data from IOs in 24 U.S. states. Our study area focuses on the four Westernmost regions of the U.S.: Northwest, Pacific, Eastern Rockies, and Southwest, as is shown in **Figure 1.**

We focus on these regions because of the reliance on surface water IOs relative to the High Plains or Eastern regions. The SIO received a response rate of 44%. This novel data is the first nation-wide data collection effort aimed at IOs since the 1978 Census of Irrigation Organizations (CIO). We are unable to link SIO and CIO responses for a few key reasons. First, the time gap between surveys hosted changes in eligible IOs, such as through dissolutions or new formations of IOs, as well as a difference in the types of IOs targeted by each survey. Second, differences in scope and survey design restrict our ability to draw direct comparisons between responses. Having access to current data and

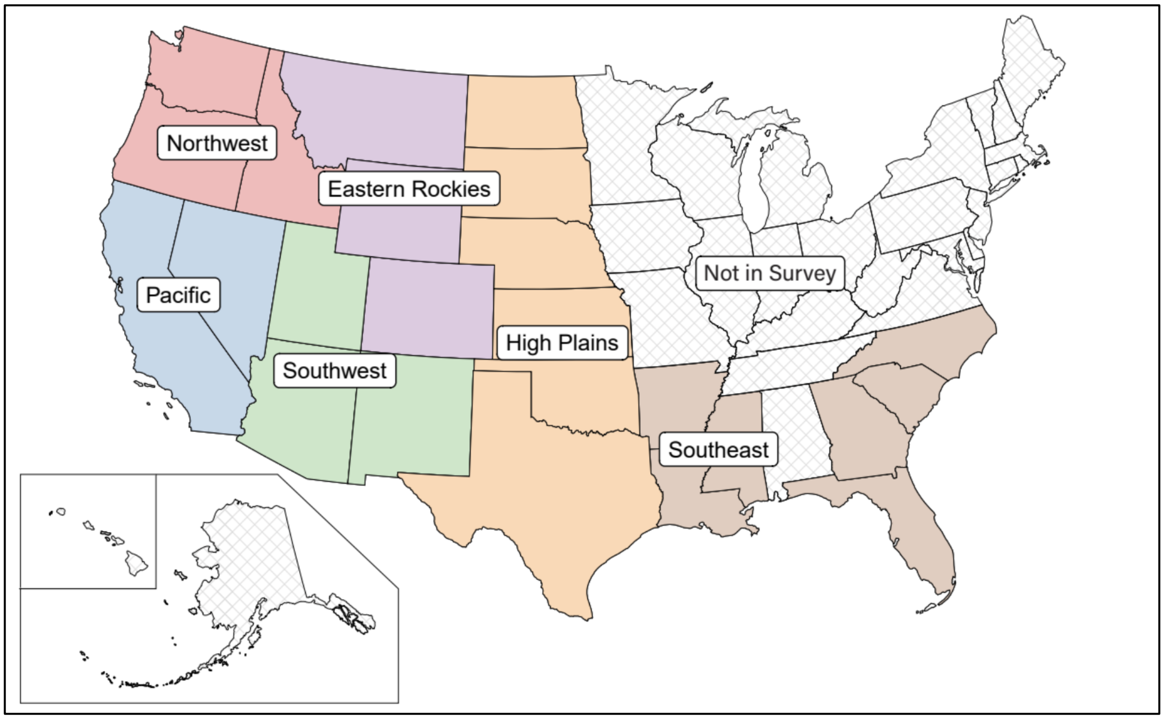


**Figure 1. Survey of Irrigation Organization (SIO) Study Areas**
*Source: USDA, Economic Research Service (USDA, NASS, 2020).*

information about IO structure and behavior is a crucial component of effectively mitigating the consequences of increasing water scarcity in the agricultural sector. The information collected by the SIO includes questions pertaining to governance structure, investments, user participation, and organizational characteristics.

Our model includes many variables that are sourced from the SIO. **Table 3** provides summary statistics of key variables included in the empirical model. The outcome variables we use in our model are binary variables representing whether or not an IO made an investment in a particular adaptation specifically for the purpose of conserving water within the five years prior to SIO collection.[1] We focus on investments made in conveyance improvements – lining canals or replacing open canals with piping – and investments made in measurement technology for water flow within the system. Additionally, we include an outcome variable that indicates whether any investments were made for the purpose of conserving water, including funding cost-share programs for on-farm adaptations, financing the fallowing of irrigated land, investing in the improvement of storage or diversion reservoirs, and "other" conservation investments, as

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[1] Although the SIO does contain questions concerning IO's investments in water scarcity adaptations in dollar amounts, the responses are largely incomplete. We opt to use binary outcome variables to maximize sample size for modeling purposes. Our chosen survey question for these variables reads: "Using its own funds, in the last five years did this organization make the following types of investments to conserve water?" A full copy of the SIO can be acquired through NASS.

**Table 3. Descriptive Statistics for Key Variables**

| Variable | Description | N | Mean | SD |
|---|---|---|---|---|
| Any Investment | Binary: Made any conservation investment, 2014-2019 | 2,400 | 0.5 | 0.5 |
| Canal Lining/Piping | Binary: Invested in conveyance, 2014-2019 | 2,400 | 0.292 | 0.471 |
| Flow Rate Measurement | Binary: Invested in within-system metering, 2014-2019 | 2,400 | 0.333 | 0.455 |
| **Independent Variables** | | | | |
| Number of Farms | Farms which IO could have delivered to, 2019 | 2,411 | 6,689 | 21,447.35 |
| IO Size (100 Acres) | Acres which IO could have delivered to, 2019 | 2,411 | 103.3 | 322.12 |
| Federal Source | Binary: Receives some water from a federal source | 2,400 | 0.187 | 0.390 |
| Water Scarcity Index | Inverse Hyperbolic Sine Transformed: Avg. weeks/year 25% of county drought D2+, 2014-2019 | 2,400 | 1.879 | 1.136 |
| GW Management | Binary: IO manages groundwater in any way | 2,400 | 0.25 | 0.433 |
| Owns Reservoir | Binary: Owns a storage or return flow reservoir | 2,400 | 0.208 | 0.406 |
| Non-Ag. Uses | Binary: delivers water to non-ag. customers | 2,400 | 0.292 | 0.455 |
| User Voting | Binary: IO allows voting on key decisions | 2,400 | 0.667 | 0.471 |
| **IO Formality Level** | Categorical | | | |
| Low | Unincorporated Mutual, Other | 2,408 | 0.328 | – |
| Medium | Incorporated Mutual | 2,408 | 0.472 | – |
| High | Irrigation District, USBIA Project | 2,408 | 0.199 | – |

*Source: Survey of Irrigation Organizations, 2019; US Drought Monitor Drought Severity and Coverage Index, 2000-2023.*

*Note: Due to data confidentiality restrictions, we present weighted mean and standard deviations for all variables sourced from the SIO. These weights, provided by USDA-NASS, are representative of the entire population of Irrigation Organizatons in the U.S., and are intended to account for non-responses.*

well as investments in measurement or conveyance.[2] In our sample, we find that 50% of IOs made any type of water conservation investment between 2014 and 2019, 29% invested in canal lining or piping, and 33% invested in measurement technology.

The majority of independent variables included in our primary model are derived from the SIO. We include the number of farms to which an IO could have delivered water in 2019 as a measure of organization size. This variable is preferred over the number of irrigated acres that an organization served, or the actual number of farms that an organization served, for two key reasons. First, it ignores and temporary farm-side production decisions, like rotating to a dry-land crop or deciding not to produce in a given year. Second, it does not capture any short-term drought events that might cause an under-estimation of the scope or delivery capability of an IO. In **Table 3** we present the average IO size as a companion to farm number; the mean farm number is a relatively poor representation of the entire sample, as it is skewed by high outliers, and providing size in 100 acres helps us to better understand the true scale of an average IO. Another

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[2] We choose to highlight investments in measurement and conveyance improvements over other forms due to a limited number of observations for other investment types. Across the US, 39% of IOs invested in flow rate metering, 32% invested in canal lining or piping, 11% invested in regulating/return flow reservoirs, 8% invested in cost-sharing programs for farmers, 7% invested in "other" conservations, and only 1% invested in fallowing provisions (Wallander, Hrozencik, and Aillery, 2022). We isolate canal lining/piping and measurement as outcome variables due to their relative variation in observations.

variable of significant interest that we include in our model is a binary variable indicating whether an organization receives any water from a federal source, such as the Bureau of Reclamation. This attribute is critical in estimating adaptation likelihood because eligibility for many subsidies or cost-share programs (such as the WaterSMART program) is contingent on receiving water from a federal source.[3] Although only approximately 20% of IOs receive water from a federal source, we opt to include this variable as it is a significant divide between IO capabilities in the Western US.

We control for whether an organization was involved in managing groundwater in some way within their area of operation in 2019. This includes monitoring groundwater conditions, collecting pumping data, collecting pumping or water rights fees, permitting new well development, and managing groundwater recharge or quality. We assume that if groundwater is available in the organization's area of operation, they will be involved in its management in some capacity. Approximately 25% of irrigation organizations in our

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[3] The WaterSMART Program, administered by the U.S. Bureau of Reclamation, assists in the planning and implementation of water scarcity adaptations. The WaterSMART program has provided funding assistance to over 2,000 projects since 2010, totaling approximately $3.2 billion in federal subsidies. Non-federal investments for these projects total nearly $9 billion (US Bureau of Reclamation). Further information about the WaterSMART program is available at the following internet sites.

WaterSMART Home Page: https://www.usbr.gov/watersmart/

WaterSMART Data Portal:

https://experience.arcgis.com/experience/bf5c5357e7044e0c80d5a55788d1db34 study area are involved in groundwater management. We include a binary variable that indicates whether an organization owns any storage or regulating reservoirs. A storage reservoir retains water for long-term use, whereas a regulating reservoir serves to capture return flows from irrigation systems to optimize short-term irrigation supply efficiency. 20.8% of IOs in our sample own at least one reservoir. We include a binary variable that indicates whether an organization serves any non-agricultural consumers. This includes residential users, industrial facilities, municipal water systems, and other IOs. Nearly 30% of IOs we consider have non-agricultural consumers.

We incorporate two key variables that represent an organization's governance structure. First, we control for whether an organization allows users to vote on key decisions. Second, we consider an organization's degree of formality. This is a categorical variable with three levels. The lowest degree of formality we consider includes unincorporated mutual organizations as well as "other" classifications (level 1). We assign a mid-degree of formality to incorporated mutual organizations (level 2). We assign the highest degree of formality to irrigation districts and projects operated by the U.S. Bureau of Indian Affairs (USBIA). A more detailed description of these organization types is presented above, in **Table 3.** These organizational characteristics are critical in estimating adaptation likelihood because they inform the ways in which an organization engages with the decision-making process. Approximately two-thirds of IOs in our sample allow users to vote on key decisions. Nearly half of these IOs are classified as incorporated mutuals, whereas approximately 33% and 20% of IOs are classified as low-formality and high-formality, respectively.

***U.S. Drought Monitor***

We use data from the U.S. Drought Monitor's (USDM) Drought Severity and Coverage Index (DSCI) to calculate a county-level drought index, representing an IO's part experience with water scarcity. The DSCI is collected and calculated on a weekly basis by the USDM, and incorporates various factors to assign a county-level drought classification. Through this "convergence of evidence" process, information including precipitation, snowpack, humidity, lake and reservoir levels, streamflow, evapotranspiration, and groundwater levels are incorporated, and are reconciled with "expert feedback" to provide a final value.

The DSCI is a weekly measure of county-level drought classification. Counties are classified based on the percentage of said county experiencing drought level D0 through D4. Although associated fire risks accompany these classifications, we summarize indicators of these classifications as they pertain to water availability and agricultural production. D0, or "Abnormally Dry," indicates either entering or exiting drought conditions and slowed crop production. D1, "Moderate Drought," indicates some level of crop damage, impacted reservoirs, streamflow, or wells, and developing/imminent water shortages. D2, or "Severe Drought," indicates the likelihood of pasture losses, common water shortages, and the implementation of water use restrictions. D3, "Extreme Drought," and D4, "Exceptional Drought," follow the same pattern, indicating widespread water shortages and water emergencies, respectively (NOAA, 2025; Svboda, et al., 2002).

Our preferred measure of water scarcity experience indicates the average number of weeks per year 25% or more of a given county experienced drought condition D2 or higher during the growing season. We restrict the time frame of this average to the 2014 to 2019 period, as this is the investment time frame that we are investigating. We then apply an inverse hyperbolic sine (IHS) transformation to this variable to better normalize it across our observations (Aihounton and Henningsen, 2019). IHS transformations of explanatory dependent variables with a heavy right skew (many zero-value observations) has grown in recent popularity among econometricians (Bellemare and Wichman, 2019). IHS transformations outperform logarithmic transformations for zero-heavy variables, as log transformations require adding a small number to zero, which can influence the regression outcomes, particularly for variables with small magnitudes. We contend that for our low-magnitude measure of weeks under a drought condition, this advantage for model robustness outweighs the complex parameter interpretation that IHS-transformations induce.[4]

**Figure 2** presents the distribution of our final IHS-transformed water scarcity measure. This shows the number of counties that are assigned certain index values. The index ranges from approximately 0 to 4. Though the IHS transformation does not entirely

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[4] In determining the best water scarcity measure for this analysis, we performed a Box Cox test which indicated the optimal transformation for the DSCI measure was a square root transformation. However, we opted to use the IHS transformation due to established econometric validity.

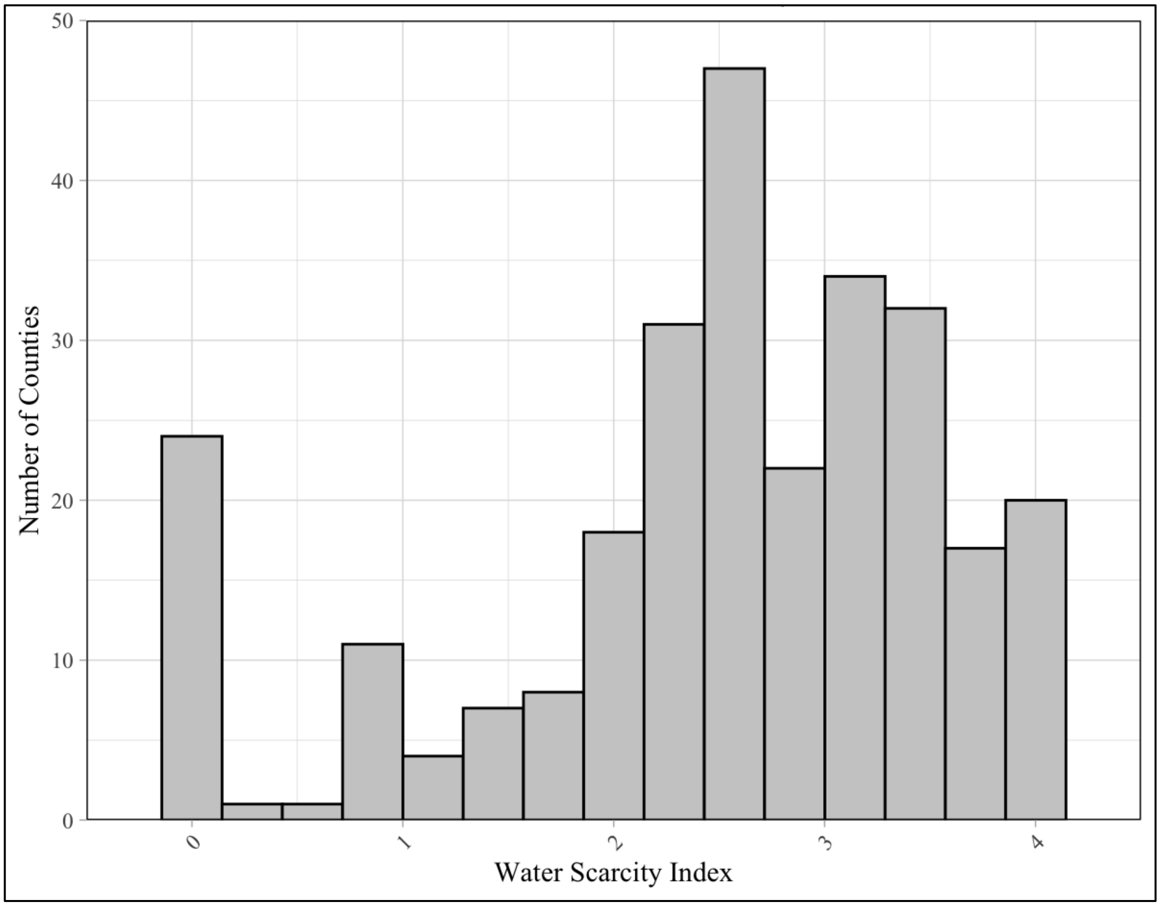


**Figure 2. Water Scarcity Index Distribution, Transformed with Inverse Hyperbolic Sine**

*Note: This considers the preferred "average weeks in D2 during the growing season, 2014-2019" measure that is described in the text.*

normalize the drought experience, it helps to address the issues of a non-transformed zero-heavily dependent variable. We display the total average "number of weeks in D2" in **Figure 3.** Importantly, the period that we consider from 2014 to 2019 captures a relatively low average annual drought frequency. Further, the distributions and trends here represent all counties in our study area, not only counties that house the IOs we consider. Due to data limitations, we present these more general figures. However, they are representative of the drought experience of the final IO sample we use in our model.

### *6.2 Methods*

We estimate the following econometric model to investigate the ways in which select organizational characteristics and experience with water scarcity influence the IO's likelihood of making a given water conservation investment. We utilize the following piecewise (linear splines) logistic regression model:

$$\Pr(Y_{ij} = 1) = f(\beta_0 + \beta_1[(1 - D_i)Farm\ Number_i + D_i K] + \beta_2 D_i(Farm\ Number_i - K) + \beta_3(Water\ Scarcity_i) + \beta_4(Federal\ Funds_i) + \beta_5 X_i + \gamma_t$$

where:

$$D_i = \begin{cases} 0\ if\ Farm\ Number_i < K \\ 1\ if\ Farm\ Number_i \geq K. \end{cases}$$

The outcome variable $Y_i^j$ represents the probability that IO $i$ invests in adaptation j, j={Any Adaptation, Flow Rate Measurement, Canal Lining/Piping}, with a possible outcome of 0 (did not invest) or 1 (did invest), and f(.) is the logistic cumulative distribution function (CDF). This model specification allows for a nonlinear effect in the estimated effect of farm number at a manually specified threshold $K$. $Farm\ Number_i$ is a

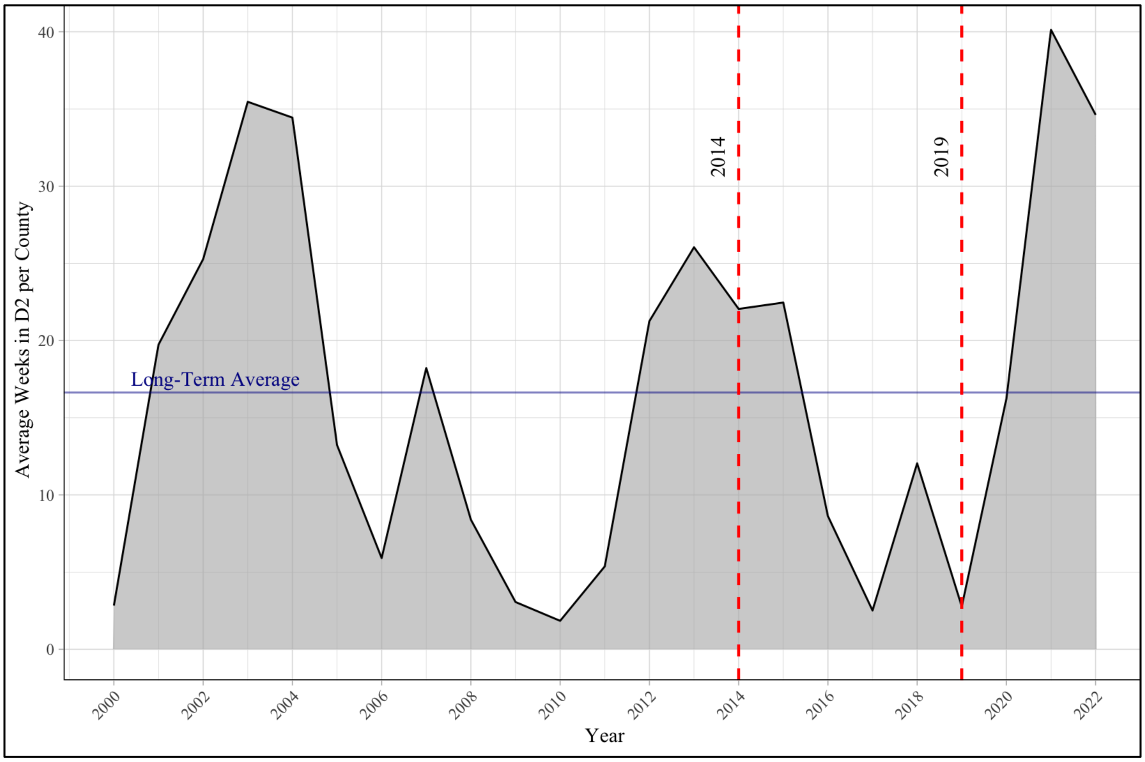


**Figure 3. Average Weeks in D2+ Drought in the Western US, 2000-2023 Growing Season**

continuous variable defined as the number of farms or ranches that an IO could have delivered water to in 2019. $\beta_1$ represents the estimated impact of IO size on $Y_{ij}$ when the number of farms is less than threshold *K*, and $\beta_2$ represents the estimated impact when the number of farms exceeds *K*. The inclusion of this piecewise linear spline results in separate slopes above and below the K; we are thus better able to identify nonlinearity in the impact of organization size on the probability that $Y_{ij} = 1$. The indicator $D_i$ is set equal to 1 when $Farm\ Number_i \geq K$ and 0 otherwise, which allows the slope to shift at *K*.

$Water\ Scarcity_i$ represents the IO's past water scarcity experience, capturing the decision-making period from 2014-2019, whose creation is described above. $Federal\ Funds_i$ represents whether IO i receives water from a federal source, which makes them eligible for federal funding assistance for adaptation investments. These effects of these two key variables of interest are captured by parameters $\beta_3$ and $\beta_4$, respectively, representing how changes in water scarcity experience and policy-driven assistance impact an organization's likelihood of investing in adaptation j. $X_i$ represents a vector of other organizational characteristics, such as governance structure, non-agricultural users, and groundwater management, as described above, and $\beta_5$ represents the associated parameters. $\gamma_t$ represents state fixed effects, and $\varepsilon$ represents the error term. By including state fixed effects, we control for potential confounders including state-level policies, broad differences climate, regulatory enforcement, and unobserved cultural or political characteristics that may impact both adaptation outcomes and the decision-making process of IOs.

By incorporating the piecewise component in the model, we allow the relationship between organization scale and adaptation to vary, enabling us to assess whether there might be a significant threshold for IO size that makes them more likely to adapt to water scarcity. We use the 'segmented' package in R to estimate the optimal location of a breakpoint for $Farm\ Number_i$, which applies a segmented iterative fitting algorithm to refine the predicted breakpoint (Muggeo, 2003). In applying this method for selecting optimal breakpoints, we begin with our standard logit regression. The algorithm is applied to the predictor, $Farm\ Number_i$, and begins by setting an initial "test" breakpoint, splitting the data into observations above and below that point. It iteratively tests for points where the slope of the relationship changes. It attempts to minimize the deviance (based on log-odds) for our logit model between the two groups. (Muggeo, 2003; Muggeo, 2008). This process allows us to identify an optimal breakpoint for our linear predictor.

We perform this test for each adaptation and assign the following breakpoints K: We estimate the optimal threshold for making any adaptations is 60 farms, for investing in measurement is 56 farms, and for investing in canal lining or piping is 194 farms. This aligns with our conceptions about the relative price of making these investments. For lower cost investments, fewer IO members would need to pool their resources to make the investment the optimal decision, compared with a higher number of IO members for higher cost investments.

## 7. RESULTS AND DISCUSSION

**Table 4** displays the marginal effects for our piecewise logistic regression. We regress multiple explanatory variables on an organization's adaptation likelihood, as described above. Results are presented as estimated marginal effects specific to different adaptation investment types: whether the IO made any adaptation, invested in lining or piping, or invested in flow rate measurement. Several independent variables exhibit strong associations with our selected adaptation outcomes.

Our results indicate that for all three selected adaptation investments, the number of farms that an IO has the capacity to serve, or IO size, is significant and positive. This result is backed by numerous robustness checks, displayed in Appendix A. Organizations that have a greater number of users or members are likely to have greater financial resources to make these high-cost investments, as well as a higher expected net benefit of adapting. The estimated marginal effects of IO size below and above threshold K indicate that the effects of size are stronger below the knot, suggesting that the adaptation likelihood of smaller IOs is more responsive to an increase in size than that of larger IOs. This suggests IOs experience diminishing returns to scale, and aligns with Leonard and Libecap (2019) who investigate the effects of IO size on the scale of historical irrigation infrastructure development. They find evidence suggesting increasing IO size by one water user increased user-average ditch length, "possibly because of returns to scale in the presence of high fixed costs" (Leonard and Libecap, 2019; pp. 89-90). Our results mirror this finding. By further decomposing the size effect, we find evidence of a nonlinear relationship between IO size and adaptation likelihood; while the magnitude of

**Table 4. Marginal Effects for the Piecewise Logistic Regression**

| Variable | Any Investment | Measurement | Lining/Piping |
|---|---|---|---|
| Size Below Threshold | 0.0032*** | 0.0025*** | 0.0006** |
| ($< K$) | (8e-04) | (7e-04) | (3e-04) |
| Size Above Threshold | 0.0002* | 0.0001* | 0.0002** |
| ($\geq K$) | (1e-04) | (1e-04) | (1e-04) |
| Water Scarcity Index | 0.0389*** | 0.017 | 0.0392*** |
| | (0.014) | (0.0131) | (0.0134) |
| Federal Water Source | 0.0971** | 0.1306*** | 0.0868** |
| | (0.043) | (0.0372) | (0.0366) |
| IO Formality Level | 0.0591* | 0.1128*** | 0.0961*** |
| | (0.0356) | (0.034) | (0.0336) |
| User Input (Voting) | 0.2819*** | 0.2994*** | 0.2909*** |
| | (0.1018) | (0.1016) | (0.102) |
| Voting × Formality | -0.1243*** | -0.1446*** | -0.1263*** |
| | (0.0447) | (0.0427) | (0.0425) |
| Groundwater Management | 0.1539*** | 0.1619*** | 0.0023 |
| | (0.037) | (0.0321) | (0.033) |
| IO Owns Reservoir(s) | 0.1385*** | 0.1571*** | 0.0222 |
| | (0.0384) | (0.0331) | (0.0336) |
| Non-Agricultural Users | 0.0627* | 0.0368 | 0.1354*** |
| | (0.0339) | (0.031) | (0.0303) |
| Nonprofit | 0.1123** | 0.0415 | 0.0639 |
| | (0.0466) | (0.0414) | (0.0409) |

*Note: Standard errors are reported in parentheses*
** p < 0.10, ** p < 0.05, *** p < 0.01*
*Our estimates are presented as average marginal effects for binary and continuous variables, and as conditional marginal effects for categorical variables (Ai, C. and Norton, E. C., 2003; Williams, R., 2012). Raw results of our estimations, meaning the marginal effects were not calculated, are presented in the appendix.*

effect is greater for smaller IOs, this approach also reveals that increasing the size of a large IO still increases adaptation likelihood, just to a lesser degree. We present a specification of this regression without the piecewise effect for comparison in Appendix A, **Table 6 and Table 7.**

The Water Scarcity Index variable captures the extent to which an IO experienced severe drought conditions or higher during 2014-2019, the decision-making period of focus for the SIO. Our results indicate that a greater experience with short-term water scarcity is significantly associated with an increase in the likelihood of investing in canal lining or piping. We can assume that the majority of the impact we observe for making "any adaptation" is attributable to the effect on canal lining or piping. Since this index is transformed using the inverse hyperbolic sine function, interpretation is indirect. However, we can recover the interpretable effect of a one-unit change in the original value.[5] We find that at the median level of drought exposure (2.25 weeks per year), an

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[5] We recover the marginal effect for the IHS-transformed drought scarcity index following Bellemare and Wichman (2020).

$$\frac{dy}{dx} = \beta \times \frac{1}{\sqrt{x^2 + 1}}$$

where $\beta$ represents the estimated average marginal effect of the IHS-transformed water scarcity measure, and $x$ represents the value of the original variable (Bellemare and Wichman, 2020). Using the median number of average D2 or greater drought weeks (during growing season) per year impacting at least 25% of an IO's county – 2.249 – we can estimate an approximate impact.

additional week of annual water scarcity during the growing season, in which 25% or more of the county experience D2 or worse drought, is associated with a 0.69 percentage point increase in the probability of canal lining or piping investments, and a 1.58 percentage point increase in the probability of investing in any water scarcity adaptation. These results indicate that near-term exposure to drought events during the growing season is a driver of investment in water conserving improvements to conveyance infrastructure. Because the 5-year period captured by the index is the same time frame in which these adaptation decisions were made, we can conclude that these results reflect IOs responding in real time to drought exposures. This supports the notion that drought events are more likely to cause reactive investments by organizations than to spur longer term planning for future scarcity. However, this discrepancy between canal and measurement improvements may also reflect a lagged response in observed adaptation outcomes to water scarcity.

Measurement outcomes are often a precursor to costly canal improvements (Hrozencik, et al., 2025). Our study period may be capturing canal investments for IOs that previously invested in flow rate measurement: we may be observing the implementation phase for IOs. In this alternate interpretation, the lack of a significant association between measurement investments and water scarcity experience may be a reflection of our model's time scale limitations.

Overall, our findings support the idea that water scarcity imparts a positive effect on the expected benefits of investment. The value of conserving water increases with the experience of water scarcity, particularly for IOs with high dependence on surface water or with wasteful conveyance infrastructure. This may sway the balance of adoption as the perceived threat of drought-induced loss rises. Intuitively, IO members incur greater losses during severe drought periods, and may thus have a greater incentive to support off-farm adaptations to water scarcity.

Access to a federal source of water, typically provided through U.S. Bureau of Reclamation Infrastructure, has a positive and significant association with adaptation likelihood across all three adaptation types. We attribute this result to eligibility for federal support programs granted to IOs who receive federal water. Receiving at least some water from a federal source increases the likelihood of making any adaptation by 9.71 percentage points, measurement investments by 13.06 percentage points, and conveyance improvements by 8.68 percentage points. These results suggest that access to a federal water source – and therefore access to federal funding sources – is associated with a broad increase in the likelihood of investing in infrastructure improvements. Given the capital-intensive nature of making these adaptation investments, these results reflect the reality that access to federal financial support effectively reduces the cost of investment, implicitly increasing the net benefit of adoption.

We observe distinct effects of IO governance structures on adaptation likelihood. Our results suggest that IOs with a higher level of formality have an average increased adaptation likelihood of 5.91 percentage points for making any adaptation, 11.28 percentage points for measurement investments, and 9.61 percentage points for canal lining and piping. This is likely due to a correlation between federal water access and IO type; irrigation districts, which are classified as the highest level of IO formality, are typically recipients of federal water. Our results also indicate that IOs that allow users to vote on key decisions are between 28.19 and 29.94 percentage points more likely to invest in water scarcity adaptations. This suggests that participatory governance heavily increases an IO's responsiveness to water scarcity; if IO members are involved in the decision-making process through a bottom-up approach, they tend to be more likely to support adaptations (Ostrom, 2002). However, the interaction between IO formality and voting provides further insight into this relationship. The negative and significant effect of this interaction term suggests that for more formal IOs, voting may become counterproductive for water scarcity adaptation investments. This result could be explained by the embedded nature of decision-making powers in more formal or historically long-established IOs; voting may exclude non-landowners, or be weighted by land value, thus skewing voting outcomes towards entrenched interests. Although this structure tends to favor agricultural producers, these parties may resist changes unless they are mandated or subsidized (Owen, 2024). This interpretation is backed by the concept of "institutional path dependence;" with constituents and stakeholders facing uncertain outcomes of adaptation, they are unlikely to support institutional changes that are perceived as risky, especially when they come at a high upfront cost (Libecap, 2011). This is especially pronounced for IO members with vested interests in maintaining the status quo (Cody, et al., 2015).

An important caveat to note regarding the association between water scarcity experience and investments in canal lining or piping, as well as the lack of association with measurement, may be reflecting the sequence of decision making rather than a distinct affiliation with one type of response. Investments in flow rate measurement may precede investments in conveyance infrastructure, as they assist IOs in identifying areas of canals where conveyance losses must be addressed. Adaptations may not occur in a timely manner for one of two reasons: first, the actor may not recognize the need to adopt long-run adaptations in the short term, and second, the opportunity for long-run adaptation may not be present in the short run (Burke and Emerick, 2016). Due to data limitations, we are not able to observe if or when long-run adaptations to water scarcity were adopted prior to 2014. This means that organizations who were able to adapt quickly after the onset of extreme drought in the 2000's, although their organizational characteristics may have lended themselves to better and more instant adaptations, are not observed as "better adaptors" in this study. For example, if an IO invested in storage or conveyance infrastructure quickly after the need to adapt became apparent, they likely invested less in these adaptations in the time frame captured by the SIO. This means that when looking purely at recent adaptations, it may appear that these organizations were less inclined to adapt than slower-acting organizations, when in reality, they simply acted sooner. IOs that have been historically exposed to drought may have already invested in measurement improvements prior to the decision-making period captured by the SIO, and could be therefore better able to respond to drought events through measurement investments.

Groundwater management is significantly associated with adaptation likelihood, though the effect is concentrated in flow rate measurement. The average marginal effect indicates that if an IO is involved in some way in managing groundwater, it is 17.7

percentage points more likely to invest in flow rate measurement. However, the effect on canal lining and piping improvements is not significant. Therefore, we can assume that the majority of the observed effect in making "any adaptation" is largely attributable to the impact on measurement. We assume that if groundwater is available in the area which an IO serves, the IO will be in some way involved in its management. These results suggest that in areas which have access to groundwater, whether as a primary or secondary water source, IOs may be more likely to invest in adaptations that allow them to track and manage their water more effectively. These IOs may have the flexibility to invest in monitoring technologies that enhance their system efficiency and meet long-term conservation targets. Further, nearly 30% of IOs that did not invest in canal lining or piping cite groundwater recharge benefits as a contributor to their decision not to invest (Hrozencik, Wallander, and Aillery, 2021).

Finally, our results suggest that IOs who serve non-agricultural users in addition to irrigators are 6.27 percentage points more likely to make any adaptation investment, and 13.54 percentage points more likely to invest in canal lining piping on average. The effect is not significant for measurement investments. We argue that this may be due to external pressures; even when non-agricultural votes carry less weight in IOs, the presence of these groups, including residential and municipal consumers, may bear significant leverage. Future research regarding this relationship is needed to elucidate the impacts of social pressures on IO decision-making. We also observe a positive and significant marginal effect for IOs that are structured as nonprofits on the likelihood of making any investment adaptations. However, this effect is likely tied with other less prevalent adaptation strategies, as it does not significantly impact the likelihood of conveyance or measurement investments. While this variable is not central to our conceptual framework, we argue that it contributes to the overall characterization of IO governance.

## 8. CONCLUSION

This study contributes to the limited literature on institution-level water scarcity adaptations in the Western US. In this study, we leveraged novel micro-level data from Survey of Irrigation Organizations (SIO) to analyze the factors that influence the likelihood of an IO to invest in water conservation adaptations. We empirically characterized long-run water scarcity adaptations made by IOs in the Western US. These results may provide timely and valuable insights for IO stakeholders and policymakers as they work towards building institutional resilience to water scarcity.

The key results of our analysis indicate that certain organizational characteristics may be more influential in determining the adaptation likelihood of IOs than tangible water shortage or drought experiences. This contrasts with farm-level adaptations, where water scarcity experience is often central in predicting adaptation outcomes. Access to federal water sources, and by association federal funding opportunities, is strongly associated with adaptation likelihood. Further, our findings suggest the presence of diminishing returns to scale, with smaller IOs showing stronger marginal responses to increases in size.

The results we discuss are explicitly not causal and should be interpreted as associative. This is due to several key limitations in our data and resulting econometric model. The SIO data used in this study is cross-sectional, thus limiting our ability to identify and control for confounders that vary over time. We cannot control for IO fixed effects, and our inability to control for these time invariant factors means that our models omit many unobservable variables. Further, while we control for a range of covariates, we are unable to link SIO observations with farm-side producer behaviors. For example, it is unclear if substitutability between farm-level and organization-level adaptations exist, and since we cannot observe what farm-level adaptations are being made by producers, we cannot control for this factor in our analysis. Finally, we do not observe IO adaptation investments made before the 2014-2019 period in question. However, due to a lack of data availability and research regarding IOs in the Western U.S., we believe that these associative results are nonetheless valuable in laying a basis for understanding their behaviors and investment decisions.

Despite these limitations, this study offers new insights to the ways in which IOs respond to water scarcity and climate change pressures. These findings are particularly relevant for policymakers in the design of future funding opportunities or incentive programs. Institution-level adaptations will likely be a critical component of ensuring agricultural resilience to climate change, both in the Western US and beyond.

# CHAPTER II

# GLOBAL IMPLICATIONS OF WATER SCARCITY IN THE WESTERN US:

# A SPECIAL CASE OF SGMA AND THE CALIFORNIA TREE NUT SECTOR

## 1. ABSTRACT

Groundwater depletion presents a growing threat to agricultural systems worldwide. In the Western US, the overextraction of groundwater endangers agricultural productivity, as producers often use groundwater as a secondary water source to sustain crop yields during periods of drought. This study focuses on California, as the state's most valuable crops, tree nuts, both rely on and contribute to rapid groundwater depletion. California is the largest tree nut producer in the world, with 70-80% of global almond trade stemming from the state. The 2014 Sustainable Groundwater Management Act (SGMA) mandates sweeping reductions in groundwater use by 2040. Current best estimates indicate that full SGMA implementation will force some level of reduction in tree nut irrigated acreage. Under the assumption that these reductions in acreage will translate directly to decreased exports, this study presents a descriptive exercise assessing the potential spillover effects of SGMA on global patterns of water use through changes in virtual water exports. We quantify historical global water use for tree nut production with and without Californian production and examine how SGMA-driven changes in land use for tree nuts may create global supply gaps. We use this exercise as a catalyst for an evidence-based discussion on the ways in which local, policy-based water scarcity interventions may influence global patterns of water use. We highlight that SGMA may push the production of water intensive crops to regions with similarly fragile water supplies. By estimating the potential for changing virtual water flows, this descriptive analysis broadens the discussion of water scarcity adaptations in the Western US to consider potential global spillovers.

## 2. INTRODUCTION

The Western U.S. faces growing challenges in sustaining future agricultural production as water scarcity, environmental sustainability, and economic pressures mount. These water challenges are not limited to the Western U.S. (Mehta, et al., 2024). Globally, agriculture accounts for nearly 70% of freshwater withdrawals (surface water and groundwater), and water shortage affects approximately 40% of the world population (Ingrao, et al., 2023; Lenzen, et al., 2013). Groundwater depletion is widespread, with accelerating rates in 30% of aquifers; high rates of depletion are most common in areas with irrigated agriculture (Jasechko, et al., 2024). Virtual water trade (VWT), a term introduced by Hoekstra and Hung (2002), characterizes the import of water-intensive commodities to water-scarce regions as a means to "export" water usage that would have occurred in local production. Virtual water is embedded in "thirsty" crops. VWT is considered to be an adaptation to water scarcity, which is implicit in the current globalized food system; countries or regions that cannot locally sustain the production of water-intensive crops, or better use their water supplies elsewhere, opt to import them to meet local demand. The U.S. is the largest exporter of virtual water through agricultural commodities (Dalin, et al., 2012). Globally, it is considered a water-abundant producer due to its developed irrigation infrastructure and groundwater availability (Dang, et al., 2014). However, as climate change continues to contribute to drought intensification, this may change.

US agricultural producers as a whole are relatively reliant on export markets, but high-value crop producers typically rely heavily on foreign markets. (USDA, 2023; USDA-ERS, 2025). High value crops tend to be water intensive. As water scarcity continues to intensify in the Western U.S., farmers adapt through various margins, including the strategic shifting of cropping patterns or by fallowing land. In the case of irrigated high-value crops, this results in decreased production and thus decreased exports. This has negative consequences for both domestic producers, in the form of decreased profitability, and global consumers. This global landscape poses a further incentive for water scarcity adaptation in the Western U.S.

In many areas of the Western U.S., surface water scarcity and variability command a high level of reliance on groundwater. However, we observe rapid groundwater depletion in many of these regions, most notably in the Ogallala and Central Valley aquifer regions (Scanlon, et al., 2012; Jasechko, et al., 2024). The present patterns of groundwater use and reliance in parts of the Western U.S. are not sustainable for future agricultural production during drought periods.

Mitigating groundwater depletion can occur through on-farm voluntary adaptations or off-farm restrictions on groundwater use. Because groundwater is a classic common-pool resource (CPR), however, users are motivated to over-extract the resource (Hardin, 1968). Policy intervention is one approach to remedying this market failure. California's 2014 Sustainable Groundwater Management Act (SGMA) represents a historically significant policy implement aimed to ensure long-term sustainable groundwater management (California Department of Water Resources). This new policy pressure is forcing adaptation not only through explicit directives, but by further limiting the amount of water available for agricultural production in the state. In this paper, we investigate the potential spillover effects of SGMA on patterns of global water use.

Coupled with projected reductions in surface water availability, SGMA implementation is projected to result in the fallowing of hundreds of thousands of irrigated acres in California (Burlig, at al., 2024; Hanak, et al., 2023; Escriva-Bou, et al, 2019). Land fallowing is defined as intentionally leaving a crop area unplanted, usually for a short period of time. While farmers will likely opt to fallow lower value annual crops before reducing perennial crop acreage, the production of high-value crops is projected to fall (Escriva-Bou, et al., 2023). Tree nuts are especially groundwater reliant. These crops are among the most valuable in the country, and in many cases represent critical sources in global supply chains. In 2016, Californian crops composed nearly 16% of total U.S. agricultural exports (CDFA, 2016). Virtually all U.S. production of almonds, pistachios and walnuts is concentrated in California, generating $8 billion in farm sales in 2017 (Goodhue, et al., 2020). Almonds in particular are central to California's agricultural economy, representing the state's largest export commodity; these exports comprise approximately 70 to 80% of the global almond export market. Given their water-intensive production, groundwater reliance, and export-orientation, almonds and other tree nuts serve as a notable instance of virtual groundwater trade. With projected decreases in tree nut production under SGMA and further surface water scarcity, impacts will likely extend beyond California's producers, influencing global production patterns.

Previous literature has analyzed the projected impacts of SGMA on Californian farm income, crop yields, and land use (MacEwan, et al., 2017; Dogan, et al., 2019; Cole, et al., 2024). Further, numerous studies have estimated future global virtual water trade flows. Few studies have focused specifically on the ways in which localized shocks, such as SGMA, may instigate broad shifts in water use patterns (Song, et al., 2022; Haqiqi, et al., 2023). This study contributes to the existing literature by focusing on global spillover effects of SGMA. We evaluate local responses to water scarcity within the context of a global water crisis and how they may influence changes in the patterns of global water use, an approach that we deem useful for understanding virtual water trade as an adaptation to water scarcity.

This study provides a descriptive analysis of how potential SGMA-driven reductions in US tree nut production may induce shifts in patterns of water use through changes in VWT. Using a share-weighted allocation approach, we estimate how supply gaps resulting from four supply reduction scenarios may be redistributed. We estimate what changes would be needed in major US tree nut importers, other key global tree nut producers, and net global spillover effects. These results serve as an illustration rather than a complete prediction, and highlight how local, policy-induced supply shocks may shift global water burdens. The results of our qualitative analysis highlight the global water efficiency that has resulted from California's dominance as a global supplier of tree nuts. We find that under potential reductions in US production as a result of SGMA, net global water use is likely to increase, particularly if production shifts to other water stressed countries.

The ultimate impact of SGMA on patterns of global water use will depend heavily on the ways in which Californian producers respond to the increased water availability restrictions. We emphasize the importance of effective coordinated responses at the local scale as a means to both sustain a productive agricultural sector and to minimize global burdens imposed by increasing water scarcity.

## 3. BACKGROUND

California has long stood as the US's dominant export earner for agricultural products, although the distribution of export commodities has shifted. California's tree nut exports boomed from approximately $900 million in 2000, where it ranked below fruits and other plants, to over $8 billion in 2023 (USDA-ERS, 2025). It now far outpaces all other agricultural exports in the state, indicating a strong producer response to growing global prices and demand. Approximately half of California's 8.5 million irrigated acres are dedicated to orchard crops and vineyards (Cole, et al., 2024). Although total irrigated agricultural lands are fallowed during drought periods, perennial crops appear impervious to changes in water availability.

The California tree nut sector is overwhelmingly reliant on international markets, just as international markets are reliant on California. Pistachios and walnuts are produced in other countries as well, but global almond production is distinctly concentrated in California. Although alternative exporters have emerged, none have achieved a comparable level of market dominance. On average, the state produces 70-80% of the world's almonds (Almond Board of California, 2016). However, increasing surface water scarcity coupled with rolling SGMA implementation may induce losses in market capture.

Tree nuts are both water intensive and profitable; their proliferation is evidence of California's comparative advantages for production compared to other climatically suitable areas. While tree nut production in California is threatened by growing groundwater depletion, California will likely remain the top global producer. However, sweeping adaptations to address this growing depletion issue will likely reduce production, causing some level of excess demand in the global market. In this study, we use California tree nut production and its projected declines under SGMA as a case study to explore the global spillover effects of water scarcity adaptation policies.

To discuss the impacts of SMGA on global patterns of water use, we must first understand what this landmark policy entails. SGMA was passed in 2014 with the stated initiative to achieve sustainability goals, set at the local level, in 94 threatened water basins. SGMA mandates the establishment of local Groundwater Sustainability Agencies (GSA's), who must develop Groundwater Sustainability Plans (GSP's) with a twenty-year timeframe for achieving sustainability. SGMA-impacted groundwater basins include 21 basins designated as "Critically Overdrafted," which have the highest priority, and 66 other high/medium priority basins (California Department of Water Resources, SGMA Portal). The majority of critically overdrafted basins are in the San Joaquin Valley (Hanak, et al., 2023), a key agricultural region hosting over half of California's crop production. (Escriva-Bou, et al, 2023). The ultimate objective of SGMA implementation is to prevent "undesirable results" of groundwater depletion by 2040, including chronic groundwater level declines, seawater intrusion, land subsidence, and impacts on surface water flows (California Department of Water Resources, 2017). GSP practices include investing in groundwater measurement and incentivizing voluntary cropland fallowing.

It has been over ten years since SGMA was passed into law, and we have since observed mixed success. Since SGMA was passed, California has experienced two major drought periods: the 2012-2016 drought —which SGMA was partly in response to — and the historic 2020-2022 drought. During drought periods that reduce surface water availability, farmers with access often rely on groundwater as a backup source for irrigation (Wallander, S., 2017). They often fallow land to reduce the amount of water needed for irrigation, but due to the high fixed costs of perennial crops like tree nuts or grapes, economic losses are minimized when annual crops are fallowed. However, perennial crops typically have 25-30 years of productivity, and orchards/vineyards must be retired or re-planted in these cycles.

While we expect to observe widespread reductions in irrigated acreage during drought periods in California, the observed trends in 2020-2022 reveal a more nuanced pattern in producer behavior. Annual crops (e.g. alfalfa, pastureland, rice, corn) were substantially fallowed throughout the Central Valley, with a temporary drop of several hundred thousand irrigated acres (Cole, et al., 2024). However, perennial crops saw an expansion in irrigated acreage even during this severe drought period, increasing by 200,000 acres between 2018 and 2022 (Cole, et al., 2024). Despite the substantial water requirements of these crops, their profitability seemingly outweighs producer concerns regarding drought- and SGMA-induced water restrictions. Although this trend aligns with economic conceptions of producer's profit-maximizing behaviors, it also exemplifies a key reason as to why policy intervention was necessary. Increasing perennial crop acreage limits flexibility in responses to drought periods, as fallowing productive perennial crops entails steep financial losses. Despite current trends, projections of land use in 2040, when SGMA is fully implemented, predict that there will be some level of fallowing for orchards and vineyards (Escriva-Bou, et al, 2023).

California's tree nut production provides an ideal case study through which to examine feedback loops between export -focused agricultural production and policy-induced water restrictions. The tree nut industry provides an optimal backdrop for this analysis due to the industry's geographic concentration and tangible environmental impacts. Growing global demand for tree nuts, particularly almonds, implies that reduced U.S. production (which is overwhelmingly expected due to SGMA-driven orchard fallowing) will induce increased production elsewhere. Presently, Australia, China and Turkey encroach on the U.S. almond export market share. **Figure 4** displays the trends of major tree nut exports from 2000 to 2023. Though the significance of other exporters cannot be understated, US export market share dominates that of other countries. The key competitors to U.S. tree nut exports similarly face growing water scarcity threats. Globally, the majority of tree nut production occurs in regions with high levels of water stress. Vanham, Mekonnen and Hoekstra (2020) synthesize these broad conditions. 90% of global almond production occurs under some level of water scarcity, while 80% occurs under severe water scarcity. California is the primary hotspot for production under these conditions, but countries like Spain and Iran contribute as well. Similar trends appear

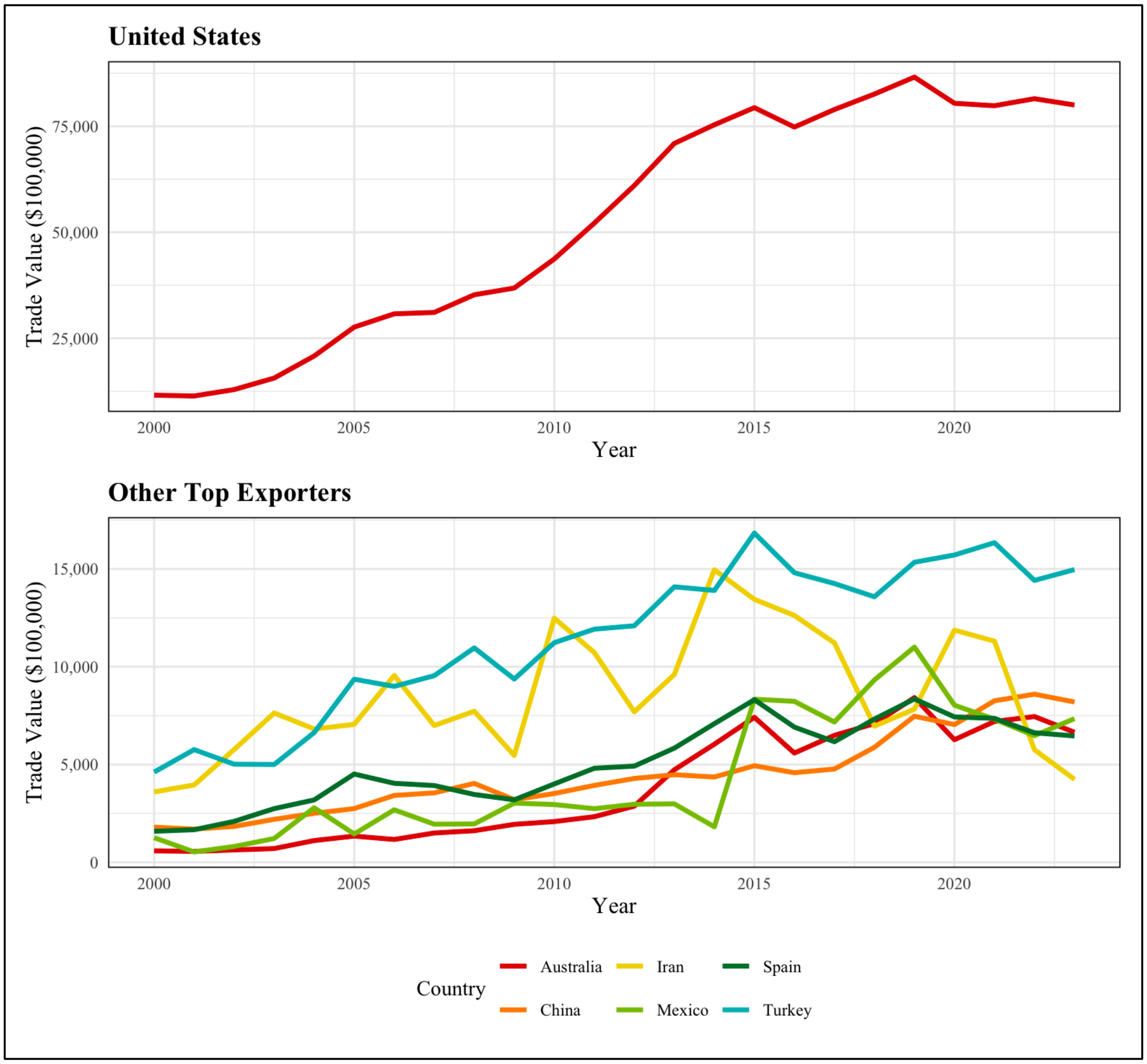


**Figure 4. Top Tree Nut Exporters, 2000-2023**
*Source: The Observatory for Economic Complexity, HS 0802 Export Values, 2000-2023*
*Note: HS 0802 includes nuts such as pecans that are not produced in California. However, the quantity and value of the US exports of these nuts is negligible in magnitude (the majority are consumed domestically.) The major US-produced nuts considered in HS 0802 are almonds, pistachios, and walnuts. 100% of almonds are produced in California, as are 94% of walnuts and pistachios.*

when examining pistachio and walnut production. 88% and 68% of walnut production occurs under significant and severe levels of water scarcity respectively, concentrated in the California, Mexico, the Middle East and China. 92% and 83% of global pistachio production occurs under significant and severe levels of water scarcity respectively, concentrated in Iran, California, and Turkey.

China is both a major importer and exporter of virtual water in the form of tree nuts and other commodities. Areas of East and North China are experiencing increasingly severe issues with water scarcity. The most water-strained regions are exporting the most water, with agricultural production accounting for 70% of total virtual water flows within and out of China (Cai, et al., 2019). Importantly China faces inefficiencies in irrigation water that far outpace those seen in the US: between 40 and 50% of water diverted for irrigation was delivered to field levels in 2001 (Jiang, 2009). Nearly 70% of China's water use for irrigation is considered "unsustainable" (Qi, et al., 2022), with China facing major groundwater depletion and quality issues (Jiang, 2009).

Countries in the Middle East also face increasing groundwater depletion issues, particularly due to annual dry periods (Buyakcangaz, 2007). Focusing primarily Turkey and Iran as major tree nut exporters, Iran is estimated to experience major groundwater depletion in nearly 80% of its agricultural areas, also largely driven by inefficient irrigation strategies. This is a major concern for domestic food security, as over 90% of groundwater withdrawals are used for irrigation (Ashraf, et al., 2021). In Turkey, underdeveloped irrigation infrastructure incurs a limitation on efficient water uses for irrigation (Buyakcangaz, 2007). Groundwater quality also poses a significant concern in the country (Cakmak, et al., 2007).

While reduced U.S. production will likely help avoid the “unwanted outcomes” of groundwater depletion locally, these impacts will likely be felt elsewhere. The regions that will likely absorb SGMA’s spillovers have little to no room for further intensification of water intensive crops.

**Figure 5** illustrates the historical trends of US tree nut exports to major trade partners. Crucially, these include other major tree nut producers and exporters, such as China, Turkey, and Spain. While this is certainly indicative of different types of tree nuts being imported versus exported, it captures various determinants of increasing demand. Growing household incomes, and a growing middle class, coupled with effective marketing of tree nuts as healthy foods, help to explain the overall growth in exports. However, for countries with the capacity to produce tree nuts domestically, this may indicate a conjunction of growing local demand and increasing domestic water supply issues.

### *3.1 Prior Evidence*

Previous literature regarding the global spillovers of SGMA is relatively limited; however, substantial prior research contributes to our understanding of the key factors at play in this dynamic. Prior research describes the local spillover effects already observed as a result of SGMA: groundwater extraction has begun shifting away from SGMA-designated “critically overdrafted” basins and towards non-regulated basins (Van Schmidt, et al., 2022). Based on this observation, it is reasonable to assume that a similar

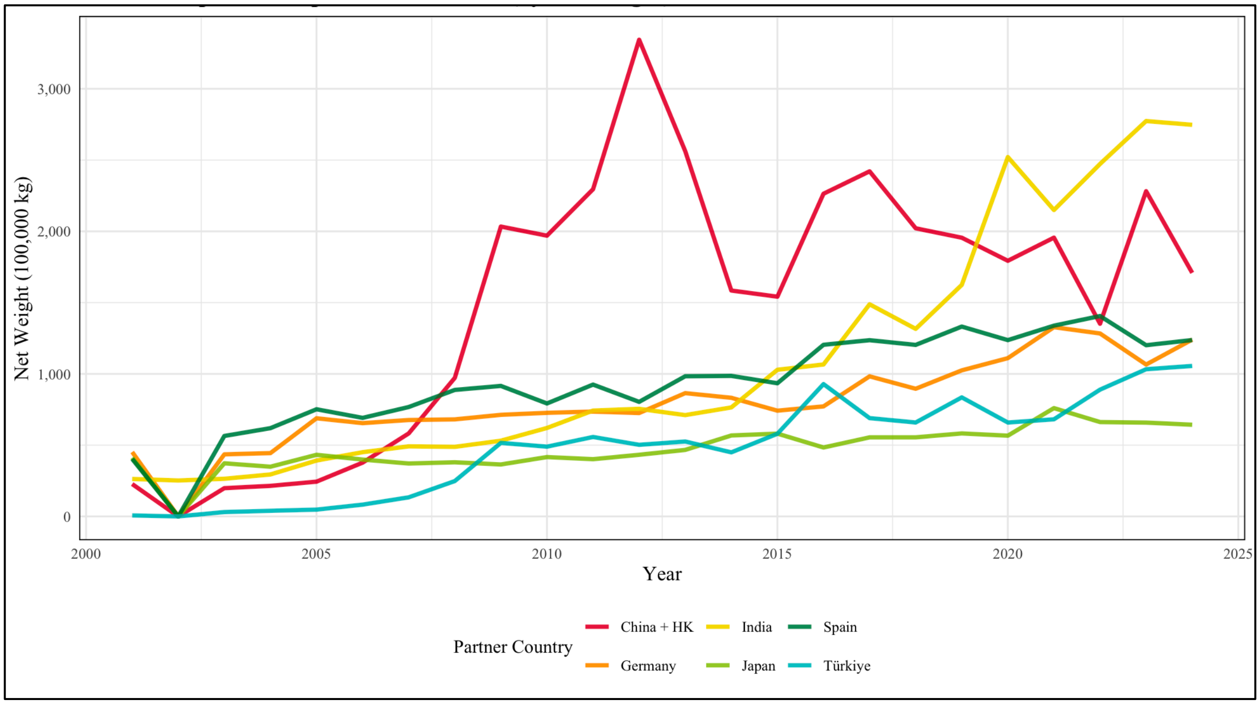


**Figure 5. U.S. Nut Exports to Top Trade Partners, 2000-2023**
*Source: UN Comtrade Database, U.S. Exports of HS 0802 (Tree Nuts)*
*Note: The "drop" in 2002 is due to missing data.*
*Because we are measuring weight traded, export quantities may over-represent consumption, particularly in India, because HS 0802 also includes in-shell nuts. These have approximately twice the weight of shelled nuts.*

trend will arise in terms of virtual water. While SGMA is a locally implemented policy, its effects will likely cause ripple effects through global trade partners, as California represents a cornerstone of water-intensive trade (Gumidyala, et al., 2017). SGMA will certainly cause declines in overall irrigated acreage, through the crops that are fallowed depends largely on the way producers adapt (Escriva-Bou, et al., 2023). Even in the highest-adaptation scenarios, fallowing of orchard crops will likely occur, and will decrease California's exports of water intensive crops. This reduction will leave global market gaps (Hartman, et al., 2021), though it is unclear exactly how big that gap will be. Other producers will likely raise their production, and this may naturally fall on onto countries that are similarly reliant on groundwater overuse for exports (Hartman, et al., 2021; Rosa, et al., 2021). This process describes VWT; countries with lower water availability can optimize their water use by importing "thirsty" crops rather than producing them locally. Focusing specifically on groundwater, however, VWT dependence by some importers may play a part in inducing groundwater depletion for the exporter (Dalin, et al., 2017). SGMA may lead to the spread of the water scarcity burden rather than a global benefit for water use (Haqiqi, et al, 2023). This paper contributes to the growing discussion surrounding global supply chain shifts that result from local environmental shocks (Graham, et al., 2023; Berrittella, M., et al., 2006; Qu, et al., 2018; Haqiqi, et al., 2023).

## 4. DATA AND METHODS

### *4.1 Trade and Production*

To conduct this descriptive analysis, we utilize data from various sources. First, we utilize trade data from UN Comtrade to measure the quantity of tree nuts exported from the U.S. to various trade partners. We consider the period from 2000 to 2023 to provide a historical overview of global trade patterns, and the period from 2018 to 2023 to provide an average baseline level of imports and exports. We use this average trade level for various calculations in our descriptive analysis. Second, we incorporate data from the USDA Foreign Agricultural Service Production, Supply and Distribution database (PS&D). We consider the same period, 2000-2023. This dataset allows us to incorporate the domestic production and exports of tree nuts by other countries. For both datasets described above, we consider commodities classified under the Harmonized System (HS) code 0802, which includes almonds, pistachios, walnuts, chestnuts and hazelnuts. Although this broader consideration of tree nuts extends beyond California's production, the vast majority are produced in California.

### *4.2 Global Water Footprint*

Measuring the water footprint of crop production at a local scale requires the analysis of multiple determining factors, such as irrigation efficiency, water sources, soil type and moisture, and evapotranspiration. We use data from Mekonnen and Hoekstra (2010) to obtain the average water footprint used to grow tree nuts in California, as well as our trading partners. This data is time-invariant: it captures only one average measure. For trading partners who do not cultivate tree nuts, thus have no observable data on water use, we use the global average of water footprint for tree nut production. Mekonnen and Hoekstra (2010) calculated water footprint using a grid-based water balance model, which incorporates average crop evapotranspiration, soil water balance, precipitation, and irrigation proportions. We use resulting data of average cubic meters of water per ton of tree nuts. The resulting data is split between green, blue, and grey water. Green water is considered to include precipitation and soil moisture, grey water is an indicator of freshwater pollution, and blue water, which is our area of focus in this study, represents the surface and groundwater consumed in crop production. For example, almonds grown in in the US have resulting proportion is approximately 18%, 31%, and 51% for green, blue, and grey water respectively. We calculate a green, blue and grey water footprint value for tree nuts grown in the U.S. by averaging the water footprint for almonds, walnuts, and pistachios.

### *4.3 Estimated Land Use Change*

Due to data limitations, we build on estimates of reduced tree nut and orchard production from a previous study (Escriva-Bou, A., et al., 2023) and accompanying report. These scenarios and estimated impacts on irrigated acreage are reported in **Table 5.** Importantly, these estimates are only considering land use in the San Joaquin Valley (SJV), where SGMA restrictions are among the strictest. However, this region also produces the majority of California's tree nuts (Goodhue, et al., 2021). Further, this data projects reductions in irrigated acreage for tree nuts and vines (majority grapes). Tree nuts are generally less economically productive than grapes when normalized by water

**Table 5. Water Reduction Scenarios (2040): Tree Nut Land Use Change**

| SGMA Scenario, 2040 (Cumulative) | Est. Land Fallowing, all crops (thousand acres) | Est. Tree Nut & Orchard Acre Fallowing (acres) | Est. Change in Tree Nut Production from baseline (2.8 million acres) |
|---|---|---|---|
| SGMA alone | 721 | 462 | 16.5% |
| + Climate Change | 800 | 539 | 19.2% |
| + Increased Surface Water Restrictions | 870 | 615 | 22.0% |
| + Water Trading | 860 – 770 | 385 – 135 | 13.7% – 4.9% |
| + Expanded water supplies of 500,000 acre- feet | 500 | 46 | 1.7% |
| + Increased Productivity | 460 | 15 | 0.6% |

*Source: Escriva-Bou, A., Hanak, E., Cole, S., and Medellin-Azura, J. (2023). "The Future of Agriculture in the San Joaquin Valley." Public Policy Institute of California, pp. 36.*
*Note: These estimates are based on a figure of estimations of land use change considering estimates of 2040. For details of the source analysis, see PPIC report (above).*
*The range in estimates for the scenario that includes water trading shows estimates for local trading to valley-wide trading.*

intensity (Cooley, H., 2015), which likely means that grapes are less susceptible to fallowing under SGMA. Therefore, we posit that our estimated percentage reductions in tree nut acreage are conservative, as they are based on a combined estimate. We assume that due to some increases in production productivity, reductions in irrigated acreage will not directly translate to reductions in production. However, we do assume that reduced production translates directly to reduced exports. Based on these projections, we assign four general (arbitrary) percent reductions in tree nut production and exports: 5%, 10%, 15% and 20%. These percents are not drawn from the scenario described in **Table 5**; we use these broad values to generalize possible outcomes given a wide range of evidence-based projections. While these reduction values do not reflect specific model-based estimates, they allow us to better understand in broad terms what different levels of land fallowing may entail for patterns of global water usage. Further, these broad-term reduction percents reflect uncertainty in the generalization of the SJV estimates to other nut-producing regions.

Under the worst-case scenario, which includes SGMA, climate change, and increased environmental flow requirements (surface water restrictions), reduced agricultural production would decrease regional annual GDP by $4.5 billion and induce 50,000 job losses in the SJV in 2040 (Escriva-Bou, A., et al., 2023). Building upon this scenario with various possible adaptation strategies, unrestricted water trading and the introduction of new surface water supplies to the region would drastically reduce the fallowing of high-value perennial crops. This is because, particularly with trading options, water could be diverted from lower value crops to irrigate tree nuts and vineyards. Local-level trading, such as between fields or nearby farms, is likely; however, valley-wide and unrestricted trading is unlikely due to political barriers and barriers with water rights transferability.

### *4.4 Methods*

The descriptive analysis that we conduct in this study provides estimates of domestic and global water use and VWT under various scenarios of reduced US tree nut production. We use these estimates to drive a larger discussion of the potential spillover effects of SGMA implementation in California. This analysis represents a descriptive exercise that is intended to produce broad estimates of how SGMA spillover effects might materialize. We examine how reductions in US tree nut exports may shift global water use patterns through VWT. We use a share-weighted framework to estimate reallocation: proportional reductions in US exports are expected to be absorbed by major importers in proportion to recent average import distributions.

Though global demand for tree nuts will likely continue to grow with household incomes, we average the quantity of US tree nut exports from 2018 to 2023 to estimate future exports, and to serve as a baseline for analyzing the export gap that would result from decreased US production. represent the baseline We apply four scenarios for reduced US production, as described above, to obtain per-country estimates of future quantity exported. We base these estimations on the 5-year historical average market share of our trading partners. We establish the baseline US export distribution, representing a percent of total US tree nut exports assigned to each trade partner, based on this average. To calculate the baseline volume of VWT (henceforth referred to as “actual VWT”), we multiply the per-country baseline export quantities by the average US blue water footprint for tree nut production. We then introduce the simulated SGMA supply constraints, a 5%, 10%, 15% and 20% reduction in export volume. In each scenario, we proportionally reduce shares exported to each trade partner in alignment with their baseline shares. For example, if a country makes up an average 10% of US tree nut exports, we assume that it will absorb 10% of the total trade volume reduction.

Next, we estimate a country-specific water gap, or the additional blue water that the country would need to use to replace the reduced US supply. We calculate this gap by multiplying the volume of “lost” US imports to the country by its average tree nut blue water footprint. These estimates represent the additional water that would need to be used by each country if they were to replace the reduced supply with domestic production. The total global spillover is then calculated as the difference between reduced US water use and total increased water use on a global scale.

We emphasize that this calculation is intended to serve as a demonstration rather than a predictive model. We rely on several simplifying assumptions, many of which are described above as they pertain to the data and variables used. This modelling exercise first assumes the proportional substitution of imports: we do not account for changing consumer preferences, volatility in trade policy and trade relationship dynamics, or non-water-based constraints on production. We also hold technology and water use efficiency constant over time. These assumptions highlight that our results represent illustrative estimates of potential spillover effects that are intended to highlight the shifting water use burden as a result of a local policy.

## 5. RESULTS AND DISCUSSION

**Figure 6** presents the actual versus potential blue virtual water trade in tree nuts from 2000 to 2023. The US Production level represents the actual water footprint used to grow exported tree nuts, and importer production represents, the water it would have taken for the importing country to produce the same quantity of tree nuts locally. For most of the U.S.'s top importers, including India, Germany, Spain and Turkey, we see that the import of US tree nuts induced a net water savings. China stands out as the exception, as domestic tree nut production tends to be more blue water efficient than US production. This may be because, despite China's irrigation inefficiency, it relies more heavily on precipitation than fresh water sources. These findings align with previous literature that finds that VWT acts as an effective market mechanism for improving global water use efficiency (Dalin, et al., 2012; Hoekstra and Hung, 2002).

It is clear that in a purely "closed economy" world, tree nut production would be immensely more water intensive than in a world with trade. Of course, even in the absence of U.S. production, most importers would not resort to producing 100% of almond consumption domestically. Other major producers would likely emerge. If, as projected, SGMA reduces irrigated acreage and production of tree nuts in California, it is reasonable to assume that other producers will increase.

**Figure 7** presents estimations of water use changes in other tree nut exporters under various scenarios of reduced U.S. production. Again, we highlight blue water explicitly, which represents groundwater and surface water. We consider the average U.S. export quantity from 2018-2023 as our baseline value of U.S. supply in this

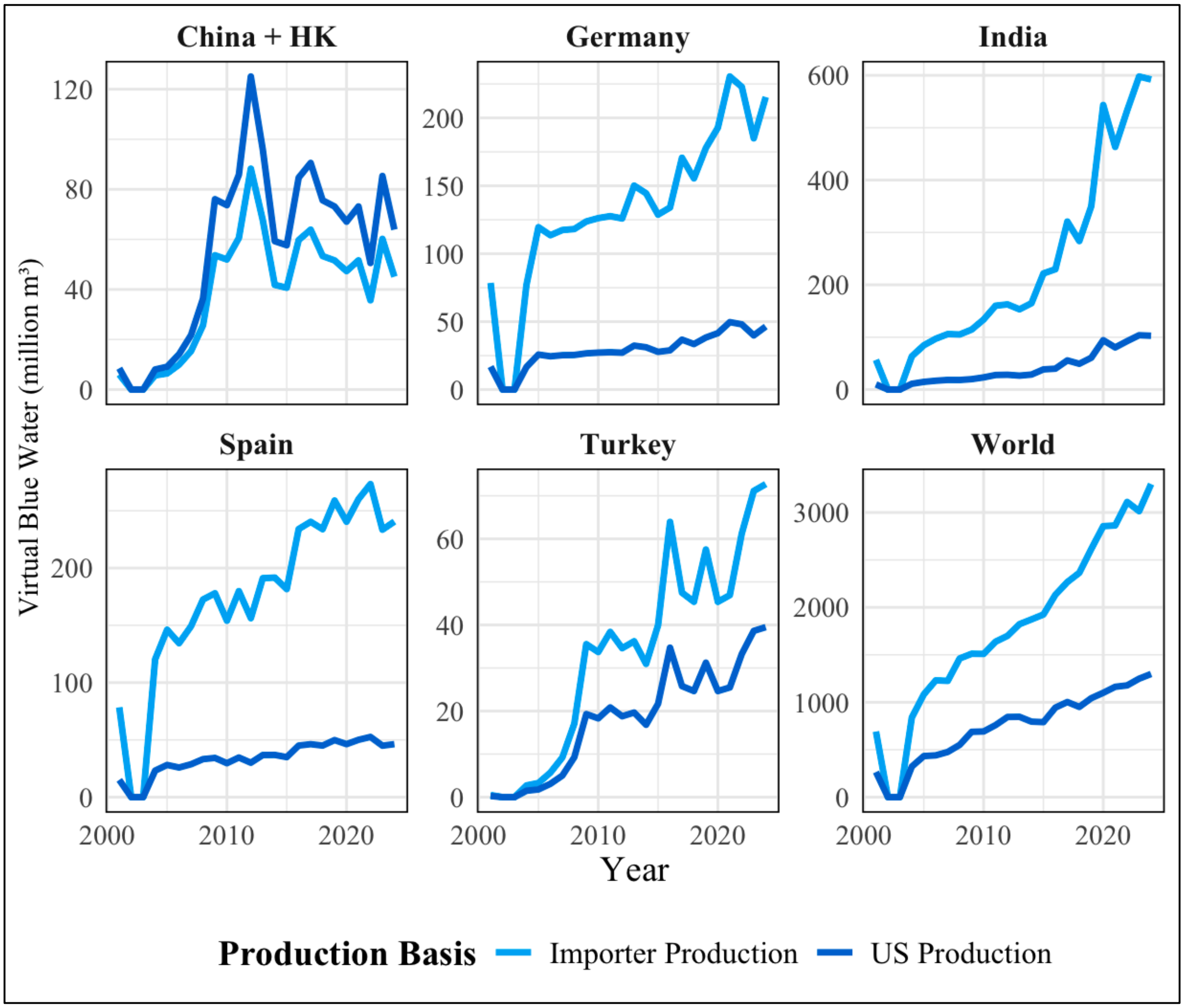


**Figure 6. Actual vs. Potential Blue Water Use for U.S. Tree Nut Exports, Top Trade Partners, 2000-2023**
*Source: UN Comtrade Database, HS 0802; Mekonnen and Hoekstra, 2010*
*Note: 'Importer Production' represents the blue water footprint that each importer would have used to produce domestically the same quantity of tree nuts that they imported from the US. 'US Production' represents the water that was used (or actually virtually traded) to produce the exported quantity.*
*Blue water describes groundwater and surface water used for irrigation.*

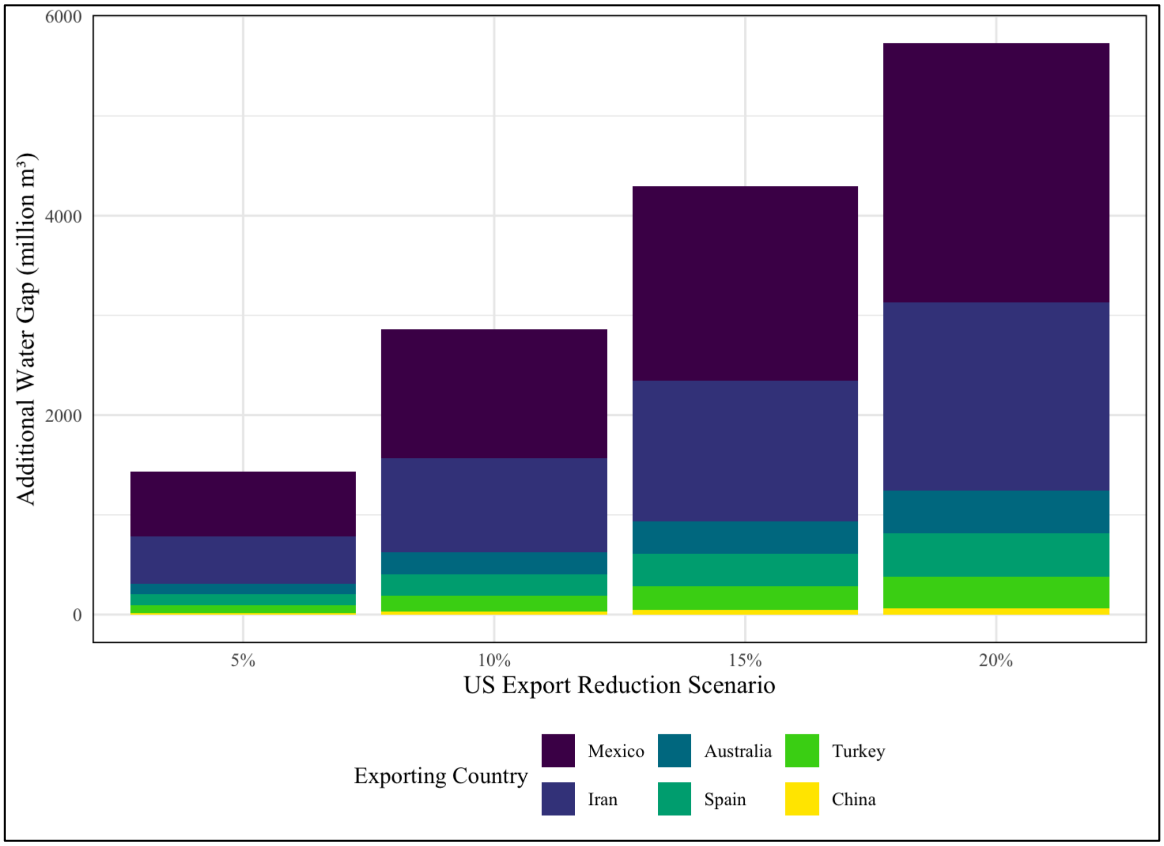


**Figure 7. Substitute Exporters' Increased Water Usage Under US Tree Nut Export Reduction Scenarios**

*Source: UN Comtrade Database, HS 0802; Mekonnen and Hoekstra, 2010; USDA – FAS Production, Supply and Distribution Database*

*Note: This figure estimates the additional blue water uses among major tree nut exporters under various scenarios of US export decline. We assign excess demand across exporters based on average 2018-2023 export market shares. We calculate increased blue water use by applying Hoekstra and Mekonnen (2010) water footprint estimates to assigned shares of the export reduction quantity.*

The trends between the two indicators for each country mirror each other, as they represent the exported quantity times the country-average blue water footprint for tree nut production, which is a country specific constant.

calculation. Similarly, we assume that the "mix" of exporters will remain consistent with the previous five-year average distribution. However, in reality this distribution will most likely shift. Production may shrink for countries who face similar water availability concerns to California.

Even in this more stylized approach, our results highlight the clear decrease in water use efficiency. **Table 11** can be found in the Appendix C, further decomposing this result. Increases in water use by other tree nut producers will likely result following reduced US exports. Shifting a higher burden of production onto other producers — most of whom operate under water scarce conditions — may ultimately raise global water use beyond what a proportional shift would indicate. Considering a parallel to the "pollution haven" concept (Copeland and Taylor, 1994), it is possible that countries with high water stress will increase production if they host less stringent environmental regulations. Uneven policy enforcement is a key consideration in discussing SGMA's spillover effects. Ultimately, the real-world shifts may magnify or mitigate this leakage effect depending on adaptations of other countries. Even under the assumption that the present exporter composition will stay constant, we highlight the likely outcome of SGMA policy leakage.

This analysis also suggests the possibility of a feedback loop in global agricultural markets. If a supply restriction impacts a major global producer, as SGMA impacts

California, this may push up global market prices. Producers in other countries would then be incentivized to expand their output, particularly in countries with lower production costs or less stringent environmental regulations (Davis, et al., 2020; Jones and Hiller, 2017; Cotrell, et al., 2019).

Ultimately, the realized spillover effects of SGMA will depend on the ways in which producers — both in the US and other key countries — adapt, more so than the policy-induced restrictions themselves. SGMA directly seeks to enable these adaptations, with many GSAs incentivizing fallowing or investments in better groundwater accounting systems. Increasing orchard acreage even throughout drought periods hints that farmers are confident in their adaptability (Cole, et al., 2024).

Although not presented in our estimations, we consider this adaptation-centered outcome is likely. Highly effective adaptation implementation would likely result in land fallowing of less than our presented 5% (See **Table 5**). We generally assume that over time, agricultural productivity increases due to improvements in technology and production practices (Wang, et al., 2024; Stifel and Minton, 2008). In California this has historically proven true, with real farm GDP doubling since the 1960s (Hanak, et al., 2018). This also reflects on-farm water scarcity adaptations such as improving water application efficiency and opting for drought-tolerant crop varieties. Further, water trading in California occurs most commonly at the local and basin levels. Local-level water trades are more likely to develop in robustness than a completely inflexible water allocation (Escriva-Bou, et al., 2023). This means that water reallocation would occur within basin sub-units, especially within water districts, allowing water use to be prioritized for the highest value uses within a relatively small region. Describing overarching resistance of irrigation districts to promote water market activity, Libecap (2011) notes that as the opportunity costs increase, these institutions will be more likely to adjust their behaviors. Thus, we argue this change in water rights trading within California will likely result from SGMA impacts. Further, the expansion of water supplies is feasible: this entails capturing more water runoff through expanding groundwater recharge efforts and reservoir expansion (Escriva-Bou, et al., 2023; Escriva-Bou, et al., 2019). It is reasonable to assume that these added water allocation flexibilities and productivity increases will — at least partially — offset reduced production capacity.

## 6. CONCLUSION

This paper serves to highlight the potential spillover effects of SGMA implementation in California. We emphasize that improving local groundwater sustainability may come at the cost of exacerbated groundwater depletion in other countries. By inducing a reduced production of tree nuts in California, SGMA will likely drive a redistribution of lost production to other countries. In any feasible production area, an increased reliance on export markets (and thus increased producer incentives) is likely to exacerbate groundwater depletion or water scarcity situations. The descriptive estimates that we present in this paper suggest that a shift in production could result in a net increase in global water use. Local policymakers should seek to weigh policy decisions in the context of both regional and global impacts. As water scarcity concerns rise globally, some consideration should be paid to these shifting environmental burdens when designing effective adaptation policies.

The ultimate effect of SGMA on global water use will depend largely on local producer adaptations. If the effective expansion of water trading regimes, further productivity increases, and water supply gains are realized, the reduced production of tree nuts in California may be minimal. This ideal outcome would help to mitigate SGMA spillovers. Aligning local water scarcity adaptation tools with global agricultural sustainability is crucial, especially considering our globalized food system. Though this study focuses on tree nut production and the SGMA policy, this study may provide a useful framework for understanding the global impacts of local water scarcity — whether that water scarcity is driven by policy instruments, climate change, or overextraction — particularly for commodities whose production is highly concentrated.

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# APPENDICES

# APPENDIX A: MODEL OUTPUTS AND ROBUSTNESS CHECKS

**Table 6. Logistic Regression Output for Presented Marginal Effects, Linear Spline (Log-Odds)**

| Variable | Any Investment | Measurement | Lining/Piping |
|---|---|---|---|
| Size Below Threshold | 0.015*** | 0.013*** | 0.003** |
| ( < *K*) | (0.004) | (0.004) | (0.001) |
| Size Above Threshold | 0.001* | 0.001* | 0.001** |
| (> *K*) | (0.000) | (0.000) | (0.000) |
| Water Scarcity Index | 0.184*** | 0.089 | 0.206*** |
| | (0.066) | (0.069) | (0.071) |
| Federal Water Source | 0.460** | 0.686*** | 0.457** |
| | (0.203) | (0.196) | (0.193) |
| IO Formality Level | 0.280* | 0.593*** | 0.505*** |
| | (0.169) | (0.179) | (0.177) |
| User Input (Voting) | 1.334*** | 1.574*** | 1.530*** |
| | (0.482) | (0.534) | (0.537) |
| Voting × Formality | -0.588*** | -0.760*** | -0.664*** |
| | (0.212) | (0.225) | (0.224) |
| Groundwater Management | 0.729*** | 0.851*** | 0.012 |
| | (0.175) | (0.169) | (0.174) |
| IO Owns Reservoir(s) | 0.656*** | 0.826*** | 0.117 |
| | (0.182) | (0.174) | (0.177) |
| Non-Agricultural Uses | 0.297* | 0.193 | 0.713*** |
| | (0.160) | (0.163) | (0.159) |
| Nonprofit | 0.531** | 0.218 | 0.336 |
| | (0.221) | (0.218) | (0.215) |
| (Intercept) | -1.714*** | -2.645*** | -3.031*** |
| (Intercept) | (0.432) | (0.487) | (0.493) |
| State FE | Yes | Yes | Yes |
| N | 940 | 960 | 960 |
| AIC | 1169.4 | 1107.4 | 1107.5 |
| BIC | 1232.4 | 1170.7 | 1170.8 |

*Note: Standard errors are reported in parentheses*
** $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$*

**Table 7. Marginal Effects Estimates for Main Regression without Linear Spline**

| Variable | Any Adaptations | Measurement | Lining/Piping |
|---|---|---|---|
| log(Farm Number) | 0.0531*** | 0.0425*** | 0.0449*** |
| | (0.0107) | (0.0099) | (0.0097) |
| Water Scarcity Index | 0.0379*** | 0.0182 | 0.0391*** |
| | (0.0137) | (0.0130) | (0.0133) |
| Federal Water Source | 0.102** | 0.141*** | 0.1062*** |
| | (0.0369) | (0.0414) | (0.0406) |
| IO Formality Level | -0.0259 | 0.0151 | 0.0105 |
| | (0.0232) | (0.0214) | (0.0217) |
| User Input (Voting) | 0.0071 | -0.0197 | 0.0041 |
| | (0.0343) | (0.0320) | (0.0313) |
| Voting × Formality (Level 1) | 0.1452** | 0.1343*** | 0.1233** |
| | (0.0620) | (0.0501) | (0.0493) |
| Voting × Formality (Level 2) | 0.0229 | 0.0095 | 0.0291 |
| | (0.0368) | (0.0348) | (0.0327) |
| Voting × Formality (Level 3) | -0.0926* | -0.1489*** | -0.0986** |
| | (0.0479) | (0.0489) | (0.0499) |
| Groundwater Management | 0.1548*** | 0.1774*** | 0.0046 |
| | (0.0352) | (0.0349) | (0.0331) |
| IO Owns Reservoir(s) | 0.1427*** | 0.1713*** | 0.0324 |
| | (0.0369) | (0.0366) | (0.0346) |
| Non-Agricultural Users | 0.0641* | 0.0409 | 0.1507*** |
| | (0.034) | (0.0317) | (0.0333) |
| State FE | Yes | Yes | Yes |
| Observations | 948 | 969 | 969 |
| AIC | 1191.7 | 1115.5 | 1128.7 |
| BIC | 1245.1 | 1169.2 | 1182.3 |

*Note: Standard errors clustered at the State level are reported in parentheses*
** $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$*

**Table 8. Logistic Regression Average Marginal Effects Estimates, Including Nonprofit**

| Variable | Any Investment | Measurement | Lining/Piping |
|---|---|---|---|
| Federal Water Source | 0.1062** | 0.1446*** | 0.1083*** |
| | (0.0419) | (0.0417) | (0.0408) |
| Groundwater Management | 0.1543*** | 0.1744*** | 0.005 |
| | (0.0354) | (0.0353) | (0.0333) |
| IO Formality Level | -0.0288 | 0.0123 | 0.0104 |
| | (0.0231) | (0.0215) | (0.0218) |
| IO Owns Reservoir(s) | 0.142*** | 0.1716*** | 0.0318 |
| | (0.037) | (0.0367) | (0.0347) |
| Non-Agricultural Users | 0.0692** | 0.0411 | 0.1528*** |
| | (0.0339) | (0.0319) | (0.0333) |
| User Input (Voting) | 0.0136 | -0.0206 | 0.0049 |
| | (0.0345) | (0.0324) | (0.0315) |
| Water Scarcity Index | 0.04*** | 0.0177 | 0.0406*** |
| | (0.0138) | (0.0131) | (0.0133) |
| log(Farm Number) | 0.0542*** | 0.0421*** | 0.0444*** |
| | (0.0108) | (0.0099) | (0.0098) |
| Nonprofit | 0.1101** | 0.0415 | 0.0633 |
| | (0.0442) | (0.0428) | (0.0437) |
| Voting × Formality (Level 1) | 0.156** | 0.1328*** | 0.1325*** |
| | (0.0617) | (0.0508) | (0.0491) |
| Voting × Formality (Level 2) | 0.0306 | 0.0082 | 0.0322 |
| | (0.0371) | (0.035) | (0.0329) |
| Voting × Formality (Level 3) | -0.0902* | -0.1483*** | -0.1052** |
| | (0.0481) | (0.0492) | (0.0502) |
| State FE | Yes | Yes | Yes |

*Note: Standard errors clustered at the State level are reported in parentheses*
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

# APPENDIX B: SUPPLEMENTARY INFORMATION

**Table 9. Irrigation Organizations by Size (Acres)**

| Organization Size | Percent of delivery organizations | Percent of water delivered | Percent that own their own reservoir | Percent from Federal Sources |
|---|---|---|---|---|
| Small (<1,000 ac.) | 44% | 2% | 10% | 6% |
| Medium (1,000-10,000 ac.) | 40% | 17% | 21% | 22% |
| Large (>10,000 ac.) | 16% | 80% | 37% | 49% |

*Source: Data drawn from: Wallander, S., Hrozencik, A. R., and Aillery, M. (2022). "Irrigation Organizations: Drought Planning and Response." U.S. Department of Agriculture, Economic Research Service, Economic Brief Number 33. ; Potter, N. A., Hrozencik, H. R., and Wallander, S. (2023). "Irrigation Organizations: Water Inflows and Outflows." U.S. Department of Agriculture, Economic Research Service, Economic Brief Number 36.*

**Table 10. Irrigation Organizations by Region**

| SIO Region | Number of Delivery Organizations | Percent that also manage Groundwater | Percent of water from a federal source |
|---|---|---|---|
| Eastern Rockies | 883 | 18% | 29% |
| Northwest | 413 | 15% | 53% |
| Pacific | 234 | 63% | 50% |
| Southwest | 909 | 25% | 27% |
| Total (US) | 2439 | 24% | -- |

*Source: Data drawn from: USDA-NASS (2020) "Irrigation Organizations" ISSN: 2692-0905; Wallander, S., Hrozencik, A. R., and Aillery, M. (2022). "Irrigation Organizations: Drought Planning and Response." U.S. Department of Agriculture, Economic Research Service, Economic Brief Number 33.; Hrozencik, A. R., Gardner, G., Potter, N., and Wallander, S. (2023). "Irrigation Organizations: Groundwater Management." U.S. Department of Agric Agriculture, Economic Research Service, Economic Brief Number 34.; Potter, N. A., Hrozencik, H. R., and Wallander, S. (2023). "Irrigation Organizations: Water Inflows and Outflows." U.S. Department of Agriculture, Economic Research Service, Economic Brief Number 36.*

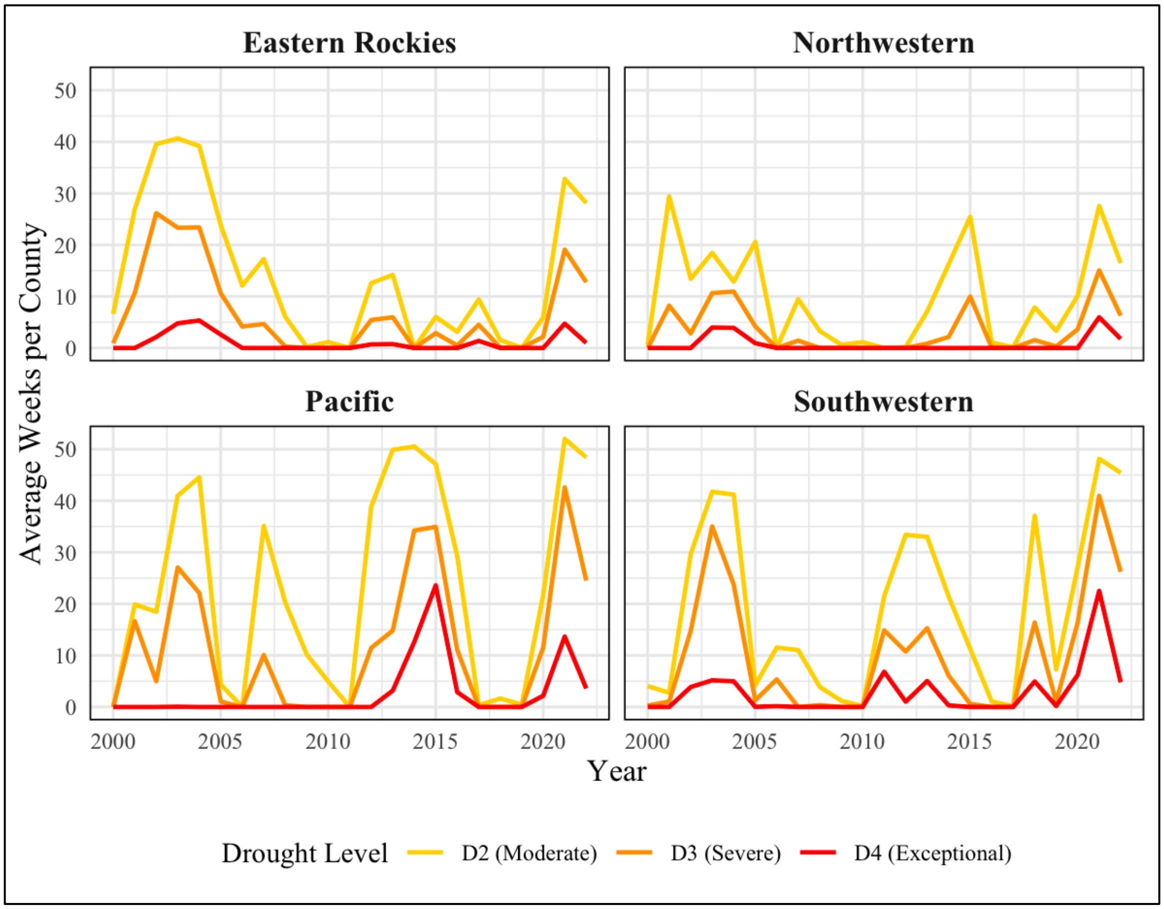


**Figure 8. Drought Classifications by Region, 2000-2023**

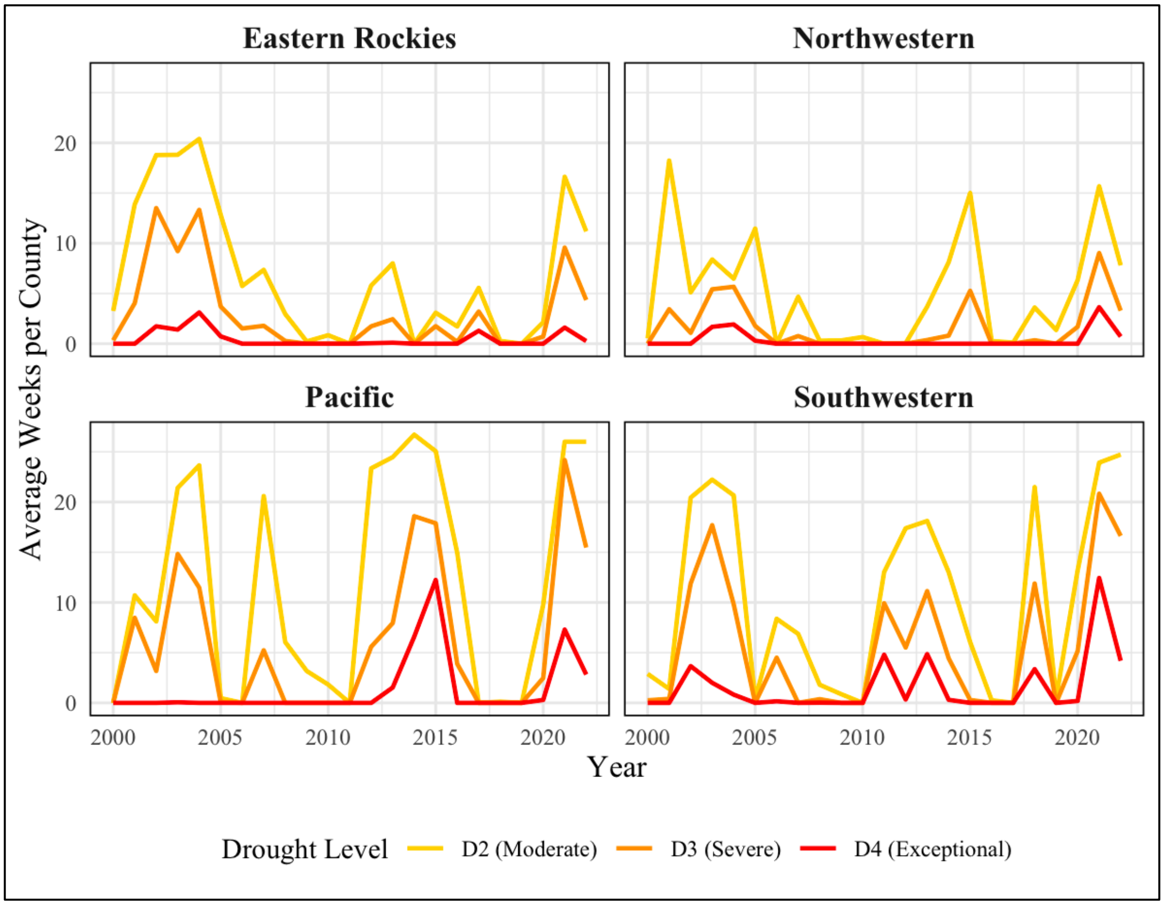


**Figure 9. Drought Classifications by Region, 2000-2023 Growing Season**

## APPENDIX C: CHAPTER 2

**Table 11. Disaggregated effects of US Tree Nut Reduced Production, Key Countries**

| Country | Avg. % US Exports | Avg. Quantity (MT) | SGMA Reduction % | Quantity Loss (MT) | Added Water (Mm3) | Net Water Change (Mm3) |
|---|---|---|---|---|---|---|
| Australia | 0.4 | 6,584.131 | 0 | 0.0 | 0.0 | 0.0 |
| China | 9.4 | 151,538.168 | 0 | 0.0 | 0.0 | 0.0 |
| India | 15.8 | 253,286.674 | 0 | 0.0 | 0.0 | 0.0 |
| Mexico | 3.3 | 53,009.852 | 0 | 0.0 | 0.0 | 0.0 |
| Spain | 8.1 | 128,389.172 | 0 | 0.0 | 0.0 | 0.0 |
| Turkey | 5.3 | 86,355.685 | 0 | 0.0 | 0.0 | 0.0 |
| USA (Avoided) | | | 0 | 0.0 | 0.0 | 0.0 |
| Australia | 0.4 | 6,584.131 | 5 | 329.2 | 972,570.4 | 1.0 |
| China | 9.4 | 151,538.168 | 5 | 7,576.9 | 18,531,046.4 | 18.5 |
| India | 15.8 | 253,286.674 | 5 | 12,664.3 | 51,608,734.1 | 51.6 |
| Mexico | 3.3 | 53,009.852 | 5 | 2,650.5 | 20,138,503.9 | 20.1 |
| Spain | 8.1 | 128,389.172 | 5 | 6,419.5 | 27,336,888.2 | 27.3 |
| Turkey | 5.3 | 86,355.685 | 5 | 4,317.8 | 10,093,929.0 | 10.1 |
| USA (Avoided) | | | 5 | 75,292.0 | -263,973,460.3 | -264.0 |
| Australia | 0.4 | 6,584.131 | 10 | 658.4 | 1,945,140.8 | 1.9 |
| China | 9.4 | 151,538.168 | 10 | 15,153.8 | 37,062,092.7 | 37.1 |
| India | 15.8 | 253,286.674 | 10 | 25,328.7 | 103,217,468.1 | 103.2 |
| Mexico | 3.3 | 53,009.852 | 10 | 5,301.0 | 40,277,007.8 | 40.3 |
| Spain | 8.1 | 128,389.172 | 10 | 12,838.9 | 54,673,776.4 | 54.7 |
| Turkey | 5.3 | 86,355.685 | 10 | 8,635.6 | 20,187,858.0 | 20.2 |
| USA (Avoided) | | | 10 | 150,584.0 | -527,946,920.7 | -527.9 |
| Australia | 0.4 | 6,584.131 | 15 | 987.6 | 2,917,711.2 | 2.9 |
| China | 9.4 | 151,538.168 | 15 | 22,730.7 | 55,593,139.1 | 55.6 |
| India | 15.8 | 253,286.674 | 15 | 37,993.0 | 154,826,202.2 | 154.8 |
| Mexico | 3.3 | 53,009.852 | 15 | 7,951.5 | 60,415,511.7 | 60.4 |
| Spain | 8.1 | 128,389.172 | 15 | 19,258.4 | 82,010,664.5 | 82.0 |
| Turkey | 5.3 | 86,355.685 | 15 | 12,953.4 | 30,281,787.0 | 30.3 |
| USA (Avoided) | | | 15 | 225,876.1 | -791,920,381.0 | -791.9 |
| Australia | 0.4 | 6,584.131 | 20 | 1,316.8 | 3,890,281.6 | 3.9 |
| China | 9.4 | 151,538.168 | 20 | 30,307.6 | 74,124,185.5 | 74.1 |
| India | 15.8 | 253,286.674 | 20 | 50,657.3 | 206,434,936.2 | 206.4 |
| Mexico | 3.3 | 53,009.852 | 20 | 10,602.0 | 80,554,015.6 | 80.6 |
| Spain | 8.1 | 128,389.172 | 20 | 25,677.8 | 109,347,552.7 | 109.3 |
| Turkey | 5.3 | 86,355.685 | 20 | 17,271.1 | 40,375,716.0 | 40.4 |
| USA (Avoided) | | | 20 | 301,168.1 | -1,055,893,841.3 | -1,055.9 |

# VITA

Hannah M. Donahue was born in Heidelberg, Germany, and grew up Jonesborough, Tennessee. After graduating from Science Hill High School in Johnson City, Tennessee, she attended the University of Tennessee, Knoxville, and received a Bachelor of Science degree in Natural Resource and Environmental Economics. She chose to continue her education at the University of Tennessee, Knoxville, pursuing a Master of Science degree in Agricultural and Natural Resource Economics with a concentration in Natural Resource Economics. Her research interest includes studying the adaptation of the agricultural sector to climate change, specifically increasing water shortages. After graduation, she hopes to continue her work in applied economics, focusing on the development, evaluation, and implementation of climate change adaptation practices in the agricultural sector.