Margins of adaptation to water markets:

Evidence from Chilean fruit production

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Abstract

Current levels of water extraction worldwide are unsustainably high, and agriculture is major contributor to this rate of use with over 70% of water extraction going to irrigation. While these facts have prompted interested in how environmental policies such as water markets can prompt cost–effective reductions in the water–intensity of agriculture, little is known about how farmers adapt to the marketization of water and the consequences of these markets for the food production landscape. I use spatial and temporal variation in water market activity in Chile, where the privatized water rights system is arguably the most laissez–faire in the world, to provide causal evidence on how farmers respond to water markets. I find limited evidence that water marketization induces investments in precision irrigation technology, and that farmers' principal channel of adaptation is through crop switching to less water–intensive crops.

1 Introduction

Rising demand for water coupled with climate–change induced shifts in the availability of freshwater has caused growing scarcity of freshwater supplies (Gleick and Ajami, 2014; Peña et al., 2004). These changes have hit both surface and groundwater sources; aquifer levels around the world are falling, and the rate of groundwater extraction in several countries must decrease in order to prevent aquifer collapse (Jasechko and Perrone, 2021). The human element of increased extraction has come from all sectors, but agriculture is the major contributor to water demand and extraction with over 70% of water use worldwide going to irrigation (Boretti and Rosa, 2019). While many factors contribute to the water intensity of agriculture, regulation is a key determinate: water in many parts of the world is incompletely regulated or treated as a common–pool resource.

Economic theory suggests that water markets can induce producers to make efficient use of the resource, but little is known about how agricultural producers adapt production when faced with marketization of water rights. In many areas of the world privatization of water rights would represent a radical departure from current policy. Thus understanding how farmers adapt to water marketization is an important question for understanding least–cost channels for making agricultural production more sustainable when markets are not viable, and can have implications for the design of the market itself. This paper attempts to fill this gap by providing empirical evidence on changes in farm production when water use rights take on market value from Chilean agricultural production.

I study the effects of water markets on adaptation behavior in the context of Chilean fruit production. While the focus on fruit is a product of data availability, fruit production constitutes the largest share of agricultural output in Chile (Retamales and Sepúlveda, 2011), and represents the lion's share of irrigated land. Chile is an interesting context in which to study water markets because Chilean water rights are among the most laissez–faire in the world; in this context, rights are fully privatized, permanent and tradeable with few restrictions (Donoso, 2013). Importantly, these rights are decoupled from land, making their permanent sale as a right to a flow of extraction (independent of land) possible. In contrast, in riparian markets such as the American West, only spot markets for water are possible without also transferring land.

My empirical strategy exploits the fact that these rights are continuously conceded to users by the government for free unless an environmental restriction has been put on a watershed due to over-extraction, meaning that we can think of the effective price of a permanent water use right (WUR) as being zero in the absence of a restriction. When a restriction is in place, then concessions cease and the only way to obtain a permanent right is by purchasing one from an existing rights holder. Thus, these environmental restrictions have the effect of "activating" a water market, and raising the opportunity cost of using a WUR for existing rights-holders.

In order to guide the interpretation of empirical results, I first write a stylized model of farm production in the context of a cap–and–trade regime for water. Guided by the model's predictions, I estimate the effect of water market activation, proxied by the share of a municipality under environmental restriction, on farm production outcomes. Because selection into restricted status is likely confounded by unobservable shocks to the agricultural sector, I instrument current restricted status with past drought conditions under the assumption that, conditional on current weather shocks and municipal and year fixed effects, past shocks only affect current producer behavior through the increased probability of restriction. I flexibly control for contemporaneous weather shocks to avoid contamination from serial correlation of weather shocks and provide some evidence of a limited role for anticipation of restrictions. I also conduct placebo tests using municipalities without restrictions that show that farms with no restrictions do not change current behavior in response to past weather shocks.

I test for evidence of adaptation through two main channels: irrigation technology and crop switching, and will provide some suggestive evidence for the role of extensive margin effects. I find that there is limited change in the share of land cultivated using efficient irrigation techniques such as drip and micro-sprinklers. I also find evidence that restrictions cause production to shift towards larger farms that are more likely to export, providing suggestive evidence that larger or more sophisticated farms may have higher marginal product of water. Finally, I find that farms substitute towards high–value crops of relatively lower water intensity, as the extent of water–intensive avocado production decreases in favor of an increase in less water–intensive but still high–value nuts and table grapes.

The rest of this paper is structured as follows. Section 1.1 provides a brief overview of the literature related to efficient irrigation and water markets. Section 2 provides relevant background institutional information on the structure of Chilean water markets. Section 3 describes a motivating and guiding framework of farm behavior under a cap–and–trade regime for water. Section 4 describes the data, and Section 5 presents the data and empirical strategy. Section 6 presents the results of the empirical exercise, with discussion of robustness exercises in Section 7. Section 8 concludes.

1.1 Literature review

This study stands at the intersection of environmental economics, because of the focus on water markets, and agricultural economics. Most empirical work in this area has largely focused on the case of the American West. Studies such as Buck et al. (2014), Ayres et al. (2021) and Sampson et al. (2019) exploit the fact that water rights in the West are riparian to estimate hedonic models of land prices and infer the economic value of water. These studies produce estimates of how much producers value water, or in the case of Ayres et al. (2021), are able to put a lower bound the welfare gains from trading water, but do not speak to how farms adapt to the increased value of their assets and implied increase in the shadow cost of their water consumption. Of these studies, this paper is closest to Ayres et al. (2021) in that I exploit spatial variation in a water rights system for identification, but I focus on agricultural outcomes in order to understand how producers adapt to the marketization of their extraction rights.

In this vein, Burlig et al. (2021) finds that farms are highly elastic in their response to groundwater price, with this elasticity achieved through a shift to fallowing when groundwater becomes more expensive due to increases in electricity costs which affect pumping. However, just how elastic water demand among agricultural users is not clear; Bruno and Jessoe (2021) find that groundwater demand is highly inelastic in California, and that perennial production (which dominates in my setting) is even less elastic. I conduct a similar test as these studies by using variation in the cost of water, but in my context the increased cost of using water comes from the shadow price generated by the creation of a market. Given that I do not observe water use but rather a rich set of production statistics, I focus not on calculating a water elasticity but on identifying the margins that farmers use to respond to water prices. My setting also implies that the effects are a product of prices together with the ability to reallocate water *across* farms, which is not an open channel in Burlig et al. (2021).

Finally, this study adds to the literature on the determinants of efficient irrigation adoption. Caswell and Zilberman (1985) study the determinants of the adoption of efficient irrigation technology in California using a multinomial logit model, and find that nuts (except walnuts) are most likely to adopt drip irrigation, and that groundwater access is more favorable to drip irrigation because of the ability to supply sustained pressure. Carey and Zilberman (2002) model the farm decision to adopt precision irrigation in the presence of spot markets for water and uncertainty, and find that spot markets allow farmers with small water allocations to delay the adoption of precision irrigation. This paper contrasts with these studies by providing causal evidence of the effect of water prices on adoption, and by studying the effects of markets for permanent rights on farm behavior.

1.1.1 Previous work focused on Chilean water rights

Chile's uniquely laissez–faire water rights system has attracted significant attention from international organizations and economists over the years, with both qualitative and empirical studies examining topics that range from the legal structure of the system (Vergara, 1998) to the lack of rights trading in Chile during the 20th century (Donoso et al., 2000), and case studies of the most active trading regions (Hadjigeorgalis, 2000; Hearne, 1997). Donoso (2013) and Bauer (2004) offer excellent reviews of the history of academic interest in the Chilean rights regime. These studies offer deep insight into the legal design of this system and quantification of first order statistics of the systems operation in terms of transaction costs, rights trading, and corruption. In particular Bauer (2013) discusses the fact that historically, international organizations have oversold the "success" of the Chilean system without strong quantitative evidence of the system's efficiency.

Such quantitative studies of the Chilean system are limited. Hearne (1997) uses a model of crop budgets to measure the gains from water trade in the Limarí and Elqui Valleys in Chile, and estimates that water trades result in large economic gains, especially when high–productivity farmers are the buyers. Hadjigeorgalis (2000) also studies the Limarí basin, focusing on how uncertainty influences trading behavior and the probability that a farmer will enter the market for water. As pointed out by Bauer (2004), the Limarí basin is unique in that has a large water storage capacity and well organized water users associations, implying that results from this region may not be generalizable to the rest of the Chilean water experience. This study adds to these by implementing an empirical strategy that includes most of the Chilean territory, and by analyzing the consequences of markets for a wider range of agricultural outcomes.

2 Background

The water rights regime that is currently in place in Chile was legislated in the Water Code of 1981 under the dictatorship of Augusto Pinochet. The Water Code defines water as a a national good, but ensures the security of privately held WURs, which are continuously allocated to individuals or firms by the federal government. These rights are administered by the Directorate General of Water (DGA), who must authorize rights free of charge to a user who requests them as long as the source is not over-extracted. WURs are treated as property, defined in terms of a permanent right to a flow of water, measured in liter seconds. These rights may be held over surface and groundwater, can be for consumptive or non-consumptive use,[1] and are either permanent (the flow is guaranteed) or conditional (the right is scaled proportionately in the case that flows are insufficient to meet rights over the resource). In contrast with many systems around the world, WURs are also not subject to a use it or lose it rule and are totally decoupled from land.

The full protection of WURs as a private good was meant to incentivize private investment in water infrastructure, and in particular irrigation infrastructure, which had struggled for years to generate sufficient investment (Donoso, 2013). Many studies have pointed out issues with the system, which include high transaction costs which impede trading (Donoso et al., 2000), the inability to guarantee flows for environmental services (Bravo-Sánchez et al., 2019; Peña et al., 2004), the failure to legally define "customary" rights to the water that predate 1981 (Donoso, 2013), speculation on non consumptive rights (Peña et al., 2004), and the extremely limited role of the state in regulating WURs (Bauer, 2004). In recognition of some of these challenges, a reform was passed in 2005 with the goal of limiting speculation and giving the DGA authority to consider environmental flows. The reform addressed the former by implementing a license fee for undeveloped water rights[2] and by limiting requests for new rights to demonstrated needs. The law also charged the DGA with considering environmental flows in defining new WURs (Peña et al., 2004). However, none of these restrictions applied to rights that had been conceded pre–reform.

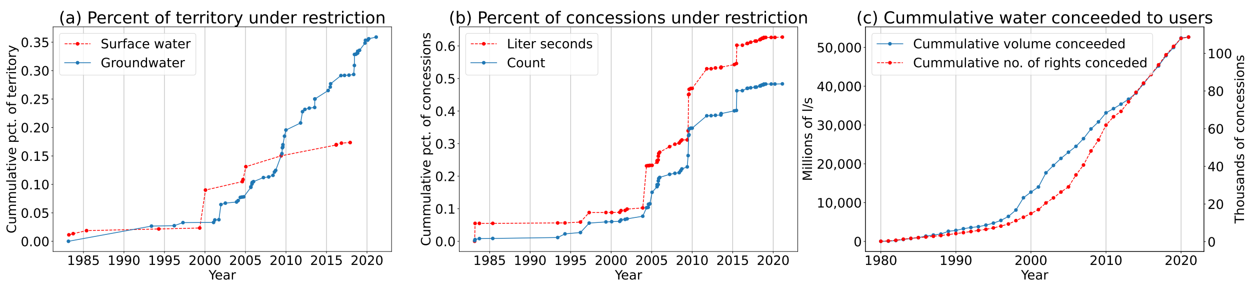
In order to request a right to extraction, a potential user must apply with the government specifying the exact geographic location, volume, and other details of extraction. The bureaucratic process of the request is done free of charge, though the potential user must pay

[1]Non–consumptive rights have an obligation to allow return flows to the source of extraction. The main motivation for the concession of non–consumptive rights is for hydroelectric development, so I exclude these rights in most of my analysis.

[2]Undeveloped rights are rights for which the user has not established a viable connection. For example, an absence of a canal to reach a surface water source or an operating well and pump system for groundwater.

for a government official to visit the site and some publication fees. This process proceeds in the absence of declarations of a restricted zone. Restricted zones are declared when the DGA determines that the rate of extraction exceeds the sustainable level. When a groundwater or surface water source is declared restricted, then the emission of government permits ends, and the only way to obtain a new right as a user is by purchasing one from other users. As Figure 1 shows, the territory and concessions under restriction has grown exponentially since 1981, with growth in restrictions over ground and surface water accelerating after 2005 when ecological flows began to be considered in the concession of new rights.

Figure 1: Restricted areas over time



Notes: Percentage of territory excludes the southern regions of Magallanes and Aysén, which are not large crop–producing areas and which have a limited number of water concessions. Calculations exclude non-consumptive uses.

My empirical strategy leverages this variation in restricted and unrestricted areas to identify the effect of water trading on irrigation technology and yields. Previous to the declaration of a restriction, there is little demand for permanent rights on the market because they are available essentially for free from the government; thus the shadow price of water is low for existing users. However once a restriction is declared, the shadow price of a water flow to an existing user becomes the highest net present value of that flow from among competing users/potential users. In this sense, restrictions raise the shadow cost of a farmer's water use, and I estimate the effect of this shadow price increase on crop and irrigation technology choice.

3 Motivating Framework

In order to guide interpretation of the empirical analysis, I develop a static model of farm behavior in a cap–and–trade like system of water use permits.[3] I use this model to generate empirically–testable predictions about farms' response to a cap being put on water rights.

3.1 Farm profit maximization

Consider a representative farm that chooses the amount of irrigation I and land L to produce a crop c according to technology:

$$q_c = A_c f(I, L; c) \tag{1}$$

where crop–specific productivity A_c can be thought of as a result of the climatic and soil advantages of the farm location. The crop–specific parameterization of f allows the relative importance of irrigation in production to vary by crop; some crops are more water–intensive than others, so the share of output dedicated to irrigation will vary by crop choice.[4] I ignore heterogeneity between farms in productivity; this would be important in the aggregate if farm exit in the face of an increase in input prices causes a shift in the distribution of input demands conditional on survival. However, given that I find no evidence of firm exit in my empirical estimates, I abstract away from this channel here.

Irrigation is itself produced with intermediate goods capital and water with CES technology:

$$I = \left(A_W (W^g + W^s)^{\frac{\sigma-1}{\sigma}} + A_K K^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{2}$$

where W^g is groundwater consumption, and W^s is surface water assumption. These are

[3] The model here is static, but given the ability of Chilean WUR holders to sell permanent rights, a dynamic model that incorporates expectations about future climate may better explain some of the facts from the data, such as the overall low volume of sales. Future work should extend this model to incorporate these dynamic effects.

[4] For example, consider the case of a Cobb–Douglas production function $q_c = A_c I^{\alpha_c} L^{1-\alpha_c}$. Here more irrigation–intensive crops would be characterized by a higher α_c.

perfect substitutes, so the farm will source water from the cheapest source available to them. For this setting, I will maintain the assumption that $\sigma > 1$ so that water and capital are gross substitutes. This captures the intuition that in order to achieve a desired level of irrigation, farmers can choose along a spectrum of irrigation schemes that range from high water and low capital bundles such as dykes and flooding, and low water but high capital bundles such as drip irrigation.

Farms are located in geographic areas indexed by $m = 1, \ldots, M$, and have access to surface and groundwater up to their WUR extraction limit, $\overline{W_m^s}$ and $\overline{W_m^g}$. Extracting and using this flow has watershed–specific costs of extraction p_m^g and p_m^s, reflecting the fact that some areas may have geographic, geological or other characteristics that cause the cost of transporting water to crops to vary.

Let the market price of a unit of ground and surface water to be λ_m^g and λ_m^s respectively. This introduces a shadow value to water use equal to λ_m^i, as in a traditional cap and trade model. Note that this shadow value may vary over geographic areas; the presence of economic or institutional barriers to trade, non–negligible costs of transportation, or information frictions would imply that the price of water may vary over space.[5] I also differentiate price between ground and surface water, as all of these frictions may be more or less intensive depending on the type of source, implying that despite being perfect substitutes, groundwater prices may differ from surface water prices and the variation between groundwater prices in different watersheds may differ from the spatial variation in surface water prices.

Assume in the short run land is fixed, and normalize $L = 1$. This simplifying normalization has the attractive property that I can now also be interpreted as irrigation per unit of land. Then the farm's problem is to maximize profits given a $C \times 1$ draw of productivities over crops $\mathbf{A}$ by choosing a crop $c \in C$, capital, and water subject to ground and surface

[5]The ideal empirical analog would attempt to characterize the variation in prices and costs in a flexible, location–specific way. The data used in this study is aggregated to the municipal level, so the municipality will be the empirical analog to an area m.

water consumption being below the amount permitted by the farm's use permits:

$$\max_{c,W^g,W^s,K} \pi_m = p_c A_c f(I;c) - r_K K - r_L + \sum_{i\in\{g,s\}} \lambda_m^i(\overline{W_m^i} - W_m^i) - p_m^i W^i \tag{3}$$

$$\text{s.t.} \quad \overline{W_m^s} \geq W_m^s \tag{4}$$

$$\overline{W_m^g} \geq W_m^g \tag{5}$$

$$[A_1, \dots A_C]' = \mathbf{A} \tag{6}$$

Given concavity of production in irrigation, for each crop c there will be a unique solution $\{W^{s*}(c), W^{g*}(c), K^*(c)\}$ that maximizes π_m; call this maximized value $\pi_m^*(c)$. If A is continuously distributed, then the mass of draws of A that yield $\pi_m^*(c) = \pi_m^*(c')$ is equal to zero, so the choice of the optimal crop c^* will be unique.

3.2 Model predictions

Given an exogenous shock to the market price of ground or surface water, farmers can adapt by changing crop choice, reducing the amount of inputs so that marginal revenue increases to meet marginal cost, or substituting towards more capital–intensive irrigation. Let W^* be the optimal quantity of ground or surface water used. If the optimal crop c^* is unaffected by the increase in price, then using Cramer's rule the response of the optimal quantity of water and capital inputs to an increase in the market price of water follows:

$$\frac{\partial W^*}{\partial \lambda_w} = \frac{\pi_{kk}}{\pi_{kk}\pi_{ww} - \pi_{kw}^2} < 0 \tag{7}$$

$$\frac{\partial K^*}{\partial \lambda_w} = \frac{-\pi_{kw}}{\pi_{kk}\pi_{ww} - \pi_{kw}^2} = \frac{\overbrace{-p_{c^*}A_{c^*}A_W W^{\rho-1} I^{1-2\rho}\frac{\partial I}{\partial K}}^{<0}\left(\overbrace{f''(I;c^*)I^\rho}^{<0} + \overbrace{(1-\rho)f'(I;c^*)}^{>0}\right)}{\underbrace{\pi_{kk}\pi_{ww} - \pi_{kw}^2}_{>0}} \lesseqgtr 0 \tag{8}$$

Intuitively, when the price that water would receives on the market rises, then the opportunity cost of using that water in farm production increases, creating an unambiguous incentive for the farmer to decrease water use in production.[6] This decrease implies a potential "substitution effect", where farms substitute towards capital in the production of irrigation, which would tend to increase capital inputs. In the model, the likelihood of this occurring is increasing in the substitutability between capital and water ($\rho \to 1$). On the other hand, if the inputs are not very substitutable ($\rho \to 0$), the farm may prefer to decrease production on the extensive margin to an extent that implies lower overall demand for capital inputs. While these choices are modeled as continuous, in reality farms choose among a discrete set of irrigation technologies that bundle capital and water intensities. Drip, for example, can be conceptualized as a high–capital and low–water bundle, sprinklers are a medium–capital and water bundle, whereas flooding can be seen as high–water low–capital bundle. If farmers begin with a bundle that is relatively water intensive, we may think of low elasticity of substitution as embodying frictions that prevent the farm from transitioning to low–water bundles, such as credit or knowledge frictions.

Which of these substitution and extensive margin effects dominates in practice is an empirical question that the next section will attempt to answer. Because I cannot observe the amount of water extracted by users, I test for substitution towards capital in irrigation by empirically testing for an increase in the share and extent of land irrigated with efficient methods. On the other hand, a decrease in both capital and water would show up as a decrease in the extent of production; i.e. a contraction of quantity produced due to firm exit or fallowing. If some firms are better able to substitute capital for water because of better access to credit or information, then we would expect an increase in the prevalence of these types of farms as a share of cultivated land as they are less likely to contract production when the shadow price of water increases. I conduct a rough test for this effect by estimating the effect of restrictions on the average plot size (in hectares), labor intensity and exporting

[6] This follows from assuming the sufficient conditions for profit to be locally maximized, $\pi_{kk}\pi_{ww} - \pi_{kw}^2 > 0$ and $\pi_{kk}, \pi_{ww} < 0$.

share.

Finally, the choice of crop c^* may change with an increase in λ^w. I assume a single crossing condition on optimal profits $\pi^*(c)$, so that an increase in water prices leads to weak substitution towards less water–intensive crops.[7] If there exist suitable substitutes in value (p_c) and productivity A_c and the cost of crop switching is sufficiently low, then empirically we would find evidence for switching to crops that thrive in a similar agroecological area and that are similar in value. These conditions motivate me to focus on three high–value export fruits of differing water intensity as potential substitutes: avocados (high water intensity), table grapes (lower water intensity) and nuts (even lower water intensity than grapes).[8]

In the following empirical work, I will test these predictions for capital intensity of irrigation, size and exporting status, and crop switching through a quasiexperimental increase in the market price of water.

4 Data

I use data from several sources, which here I group into administrative data on water concessions, trades, and restrictions; data on agricultural outcomes; and climate and weather data.

[7] Figure A.1 illustrates this property graphically. I call this "weak substitution" because it implies that if crop switching occurs then it is unambiguously towards a less–water intensive crop. For some crops, curves may not cross at all implying that given the vector of prices and productivities there is no input mix under which these would be substituted for each other. I am still working on defining the sufficient conditions on $f(I;c)$ that would guarantee this.

[8] Table grapes require about half as much water per day as avocados, but in my data are worth less than half as much per kilogram. In local currency, my data has grapes selling for an average of 676 CLP/kilo. versus 1,605 CLP/kilo. for avocados. The California Avocado Commission recommends an average of 28 gallons per tree per day for mature trees, whereas the Division of Agriculture and Natural Resources for UC Berkeley recommends 8–10 gallons per vine per day. 16 gallons a day is a rough estimate for California nut trees. California and central Chile share similar agroecological conditions, making Californian estimates appropriate for Chile.

4.1 Administrative water data

Table A.1 gives a summary of the different units of water sources in the data; restrictions are generally defined at the sub–watershed (for surface water) or aquifer (for groundwater) level, with sub–watersheds on average being about five times the size of an aquifer.

4.1.1 Concessions

Table 1: Water concessions from the government

		(1) Prop. (no.)	(2) Prop. (flow, m3/s)	(3) Avg. flow (1,000s of m3/s)	(4) Median flow (m3/s)	(5) Avg. flow (1,000s of m3/s) per user	(6) Median flow (m3/s) per user
Type	Consumptive	0.93	0.62	454.85	24.00	700.05	45.00
	Non-consumpt.	0.07	0.38	3,930.10	2,540.00	7,407.31	3,448.00
Source	Groundwater	0.52	0.00	0.29	12.00	0.45	36.00
	Surface	0.48	1.00	1,437.31	50.00	2,253.59	70.00
Use	Drinking/ domest.	0.14	0.00	2.08	35.10	2.99	54.00
	Indigenous community	0.02	0.00	1.55	60.00	2.70	169.00
	Irrigation	0.22	0.04	128.00	19.20	177.94	34.80
	Mining/ industrial	0.02	0.01	190.01	1.30	456.19	5.28
	Not specified	0.61	0.95	1,081.60	30.00	1,769.29	50.00
Condition	Conditional	0.15	0.71	3,256.73	110.00	4,976.75	150.00
	Permanent	0.85	0.29	235.57	22.50	368.33	36.00

Notes: Calculations for all rows except the "Type" section exclude hydroelectric use, and ignore rights defined as shares of an irrigation district concession, as I do not have data on how much water is implied by a share. The Column (1) reports the proportion of rights in each category as a share of the total *number* of rights. Column (2) gives the proportion as a share of the total *flow* allocated in liter–seconds. Column (3) gives the average flow in cubic meters per second per concession (user), and the last column gives the median flow (in cubic meters per second) per concession. "Conditional" rights are subject to the availability of sufficient flows from the source; in the case that the water supply exceeds the amount conceeded, all rights to that source are scaled by the same factor. Permanent rights have no such clause, and in theory the right is guaranteed.

Data on government concessions of rights are available from the DGA, and include the geographic point of extraction, the flow guaranteed by the right, the date requested and the date conceded. These data are for the initial concession given by the government, but do not reflect the size of rights post–trading. Table 1 presents summary statistics about government concessions of non–hydroelectric rights (before any kind of transaction) by type (consumptive and non–consumptive), source (groundwater or surface water), use and condition (permanent or conditional). I report both averages and medians, as a small number of concessions are very large. In particular, the median non–consumptive right allocates over 100 times the flow as a consumptive right, reflecting the fact that non–consumptive rights are generally used for hydroelectric generation. Given that use for irrigation is inherently consumptive,[9] I focus on consumptive rights for the rest of the table and the paper. Surface water concessions tend to be larger than groundwater concessions by several orders of magnitude, which is why as a proportion of total flow the surface statistic rounds up to one. This is a product of the fact that many aquifers have low volume and recharge relative to surface sources, limiting the concessions that can be made on groundwater sources. Finally, the "use" variable is unspecified in a majority of cases, but among reported uses irrigation is the most important in both number of concessions and total flow, suggesting that irrigation is an important use of water allotments.

4.1.2 Transactions

Water trades are reported in Real Estate Conservancy records, as water is treated as property once conceded to a user. Each conservancy has authority over a particular geographic territory, generally the size of one to four municipalities, and it is at this geographic level that I can identify transactions. Transactions can take the form of inheritances, gifts, donations, sales, or not reported; for the following, I consider only transactions that have a positive price associated with the record. Table 2 reports descriptive statistics about trades, aggregated to the conservancy–year level and split by restricted and non–restricted conservancy–years. Surface water sales are greater in volume than groundwater sales, which is to be expected given the difficulty of accessing geographically small aquifers from off–site. Restricted ob-

[9]While runoff may return some irrigation water to the source, this is not a guaranteeable return flow and so the right itself must be consumptive if used for irrigation.

Table 2: Water trades

A. All Sales	No restriction		Some restriction		Difference	
	Mean	Std. Dev.	Mean	Std. Dev.	Diff	t-test
Number sales	45.47	175.14	176.02	263.51	130.55***	(6.57)
Price (MM $/ ls)	0.59	4.74	1.19	10.22	0.59	(0.61)
Price (MM $/ ls), fill zeros	0.29	3.29	0.94	9.11	0.66	(1.09)
Avg. flow sold (ls)	4194.78	43201.79	5427.77	46474.48	1232.98	(0.24)
% irrig. district	0.29	0.37	0.59	0.33	0.31***	(7.94)
B. Surface water sales	No restriction		Some restriction		Difference	
	Mean	Std. Dev.	Mean	Std. Dev.	Diff	t-test
Number sales	40.76	155.44	136.52	227.61	95.76***	(5.53)
Price (MM $/ ls)	0.53	4.91	1.50	11.70	0.97	(0.86)
Price (MM $/ ls), fill zeros	0.25	3.34	1.15	10.24	0.90	(1.35)
Avg. flow sold (ls)	4429.56	44075.46	5798.07	48351.83	1368.51	(0.25)
% irrig. district	0.30	0.38	0.70	0.30	0.40***	(10.39)
C. Groundwater sales	No restriction		Some restriction		Difference	
	Mean	Std. Dev.	Mean	Std. Dev.	Diff	t-test
Number sales	1.35	5.06	23.30	54.45	21.94***	(6.49)
Price (MM $/ ls)	0.59	4.34	0.67	7.42	0.08	(0.08)
Price (MM $/ ls), fill zeros	0.14	2.13	0.42	5.93	0.28	(0.72)
Avg. flow sold (ls)	35.03	69.72	17.36	17.47	-17.67***	(-2.91)
% irrig. district	0.04	0.16	0.04	0.13	-0.00	(-0.25)
Observations	262		237		499	

Notes: Sales are defined as any transaction with a price. Prices are expressed in millions of 2010 USD. % irrigation district is identified as sales whose unit of flow is expressed in shares (*acciones* or *partes*), which indicate shares of an irrigation district's concession. The "fill zeros" modifier indicates that the average price has been imputed as zero when there are no transactions in a municipality–year

servations have a higher volume of both surface and groundwater transactions, with trading volumes increasing at least fourfold in each category. Restricted areas also appear to see increases in prices per liter–second, though this increase is smaller in relative magnitude and insignificant. Finally, while I cannot identify the use that either the seller or the buyer gave the water, I can identify transactions for which the right involved originates from an irrigation district. Identifying potential irrigators in this way, we see that irrigation district transactions are a large share of the surface water market (Panel B), making up 29% of sales in unrestricted area–years and over 50% in restricted areas. This broadly shows that restrictions are associated with more active and higher–value markets, and that irrigators are an important part of these trades.

4.1.3 Environmental restrictions

Data for constructing the area under restriction come from GIS data provided by the DGA. Figure A.2 in the Appendix maps restrictions on the Chilean territory; it is interesting to note that restrictions overlay almost perfectly with maps of Chilean agricultural production. Figure 1 plots restrictions as a percent of the Chilean territory (Panel (a)) and as a percent of concessions (Panel (b)). Both total concessions (Panel (c)) and restrictions (Panels (a) and (b)) have grown exponentially over time, and growth in the number of concessions under restriction takes off after 2005 when the reform to the water code was implemented, which allowed the DGA to take environmental flows into consideration when declaring a restricted area. Panel (a) shows that surface water restrictions are more rare and represent larger geographic areas of restriction per declaration than aquifers because they apply to a larger source of water. The fact that the number of concessions and the volume conceeded increase at similar rates indicates that there is not a strong trend over time towards larger concessions. Panel (a) is a visualization of the aggregate time variation in my treatment variable; I use the proportion of the municipality under restriction from any source to define exposure to marketization of WURs.

4.2 Agricultural outcomes

Information on agricultural outcomes comes from the Chilean Fruit Census, which is a rotating census of fruit and nut producers that includes two modules. The first provides information on the area cultivated, production in kilograms, and irrigation method by species. The second module, which is not linked to the first, provides data by crop species on area cultivated, whether or not the product is exported and how many employees the farm has. While the census includes disaggregated data at the farm level, in the public dataset observations are only identified by their municipality; therefore I aggregate all outcomes to the municipal level. Table 3 summarizes these variables at the municipal level, comparing "never treated" municipalities that have no restrictions at any point in the sample to those who were treated at some point in the sample. While treated and never treated municipalities are similar in farm size, employees and export status, they are very different in irrigation behavior and the crops grown. Treated municipalities are more likely to be irrigated with inefficient irrigation methods and less likely to be rain-fed. Among high–value fruits, they are also more likely to cultivate more water–intensive fruits such as avocados and table grapes as opposed to nuts. These facts point to potential selection into treatment, with areas with higher demand for irrigation water heading into restriction.

Table 3: Outcomes by treatment status

	Never treated		Treated		Difference	
	Mean	Std. Dev.	Mean	Std. Dev.	Diff	t-test
Avg. farm size (ha)	3.74	5.39	3.84	3.11	0.10	(0.35)
Avg. no. empl. per farm	28.84	70.36	24.68	48.30	-4.16	(-0.86)
% Exporting	0.43	0.43	0.41	0.38	-0.02	(-0.57)
% rain fed	0.09	0.23	0.01	0.05	-0.08***	(-7.95)
% Drip	0.57	0.34	0.58	0.30	0.01	(0.30)
% Efficient irrigation	0.69	0.33	0.71	0.28	0.02	(0.99)
% Other irrigation method	0.22	0.29	0.28	0.28	0.06***	(3.71)
% area cult. table grapes	0.04	0.13	0.16	0.24	0.12***	(10.58)
% area cult. avocados	0.03	0.13	0.14	0.24	0.10***	(8.88)
% area cult. nuts	0.18	0.27	0.13	0.19	-0.05***	(-3.44)
% groundwater rest.	0.00	0.00	0.16	0.31	0.16***	(12.40)
% surface water rest.	0.00	0.00	0.23	0.38	0.23***	(14.53)
Observations	564		526		1,090	

Notes: "Never treated" municipalities have no restriction declared by 2020; "Treated" municipalities are those that have some restriction declared by 2020. % Efficient irrigation includes drip, trickle and microsprinklers. % Other irrigation method includes flooding, sprinklers and furrow irrigation. All percentages are calculated as a a percent of the area of cultivated land. Each observation is a municipality–year.

4.3 Climate and weather data

Finally, I use temperature and precipitation readings from weather station monitors operated by the DGA. The two most salient climate variables that form the basis for the instrument and controls are total annual precipitation and share of days per year with a reading over 30° Celsius. These variables are constructed from daily readings from 845 precipitation monitors and 900 temperature monitors across Chile. In order to aggregate these readings to the municipal level, I take the inverse–distance weighted average of all monitors within 250 kilometers of the municipal centroid.

5 Empirical Strategy

Consider the regression of interest:

$$y_{ct} = \lambda_c + \lambda_t + \beta Rest_{ct} + X_{ct}'\gamma + \varepsilon_{cta}, \tag{9}$$

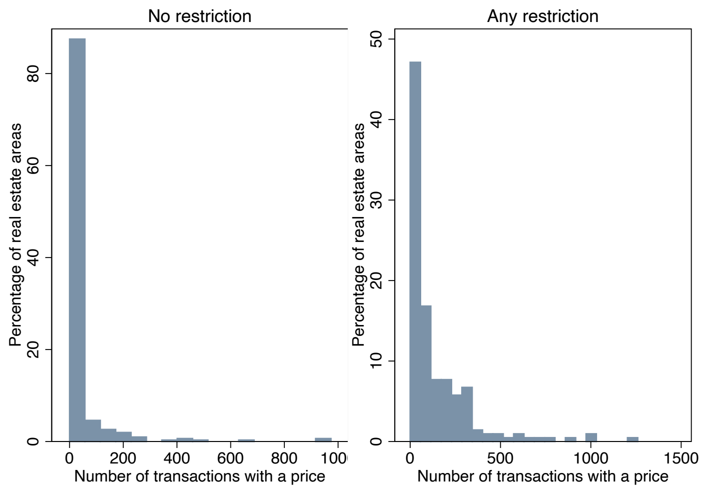
where $Rest_{ct}$ is the percent of the territory in municipality c in year t that is covered by *either* a surface or groundwater restriction, and X_{ct} controls for time–varying weather characteristics at the municipality level. I include total rainfall and the share of days over 30°C as controls, as these are the most salient determinants of water use.[10]

The intuition of this formulation is that before a restriction is in place, farms own water, but the shadow price of use λ_m is negligible because the opportunity to obtain rights from the government means that demand for water rights in the market is effectively zero. However, when a restriction is in place, other potential users of water must obtain rights from current holders, lending market value to holding rights. Thus the increase in λ_m posited in the model weakly maps to an increase in the restricted area in a municipality.

The fact that the volume and value of trades is greater in restricted areas, as reported

[10]Temperatures above 30°C have been shown to be damaging to plant health. In order to aggregate to the municipality–level from measurements taken at points, I take the inverse–distance weighted average of all values within in a 150 km. radius of the municipality centroid.

Figure 2: Restricted areas have more trading



Notes: Transactions limited to those in the sample area of the fruit census, and transactions that had a price associated with them. Counts are aggregated at the real estate conservancy level; each conservancy is composed of 4 municipalities on average.

in Table 2, gives a first hint that restrictions help "activate" water markets. Figure 2 gives us a another indication that this hypothesis is reasonable; there is a significant increase in the volume of trades in areas with a restriction, with the share of real estate conservancies reporting zero trading falling by about 50% when going from no restriction to some restricted area in the municipality.[11]

Estimated directly, β would represent the causal effect of restrictions on agricultural outcomes if, conditional on municipality and year fixed effects, restricted status is as good as randomly assigned to agricultural producers. Restricted status is not randomly assigned; by definition, municipalities with a restricted area have been identified as water-scarce. Moreover, it is likely that extraction for human use is also a strong driver of restricted status. In particular, it may be the case that an unobserved shock to a municipality both influences farmer's productivity and water extraction, which would increase the probability of a restricted area.

[11]This empirical observation may also provide evidence as to why several authors have observed that trading volumes have historically been very low in Chile (Donoso et al., 2000): as long as the government does not impose a cap on water rights, there is little to no incentive to trade.

In order to isolate my source of identifying variation from these types of unobserved shocks, I instrument the geographic intensity of restrictions using a 5–year lag of precipitation according to the first stage specification in Equation 10. The identifying assumption for this IV specification is that, conditional on contemporaneous precipitation and temperatures as well as municipality and year fixed effects, past precipitation is uncorrelated with other determinants of present day agricultural outcomes.

$$Rest_{it} = \sigma_c + \sigma_t + \alpha X'_{ct-5} + X'_{ct}\gamma + \nu_{cta} \tag{10}$$

While this instrument successfully isolates variation in water scarcity that is uncorrelated with contemporaneous productivity or other shocks to farm production, some concerns remain. For example, past adverse climatic conditions may have spurred farm exit or other adaptive behavior that continue to impact agricultural production at the time of restriction. I attempt to address this source of endogeneity in several ways in Section 7. Most importantly, I conduct a placebo test that shows that outcomes in municipalities with no restrictions are uncorrelated with lagged weather shocks, and show that there is limited evidence of anticipation of restricted status (among other tests).

6 Results

6.1 A first stage: Restrictions increase water transaction volume

As a first step, I provide evidence that restrictions are associated with more active markets. Table 4 shows the effect of the share of a real estate conservancy area under restriction on the number of sales reported and the average sale price. Because real estate conservancies are geographically much larger areas than municipalities, I was unable to estimate with precision the lagged climate variables that form the instrument,[12] so I report only the results of the

[12] Conservancies are the size of 4-10 municipalities. Aggregating precipitation data to this level results in a great loss of precision, such that the relationship between restrictions and past precipitation is weak with

Table 4: Restrictions increase water transactions

	Number of sales			Sale price (millions USD)		
	All	Surface	Ground	All	Surface	Ground
% Restricted (any)	160.614**	137.005***	0.762	0.797	0.523	0.403
	(62.700)	(51.655)	(9.771)	(1.110)	(1.285)	(0.612)
N	512	512	512	512	512	512
Mean Y	104.74	84.05	11.48	0.58	0.66	0.27

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Sales are identified as any transaction that has a price associated with it. All prices are expressed in millions of 2010 USD. Standard errors clustered at the municipality level.

two–way fixed effects specification. Restricted areas are associated with a very large increase in the volume of sales; a one standard deviation increase in the percent of the area restricted increases the volume of sales by over 50%.[13] Decomposing the effect between surface and groundwater sales shows that most of the effect is from increased volume of surface water trading. This is intuitive as groundwater sources likely face additional barriers to trade, such as being more difficult or expensive to access from other geographic locations.

I do not find detectable effects of restrictions on the trading price of transactions; restrictions are associated with large, positive, but very noisy increases in price.[14] This may be explained by highly inelastic demand for water (as in Bruno and Jessoe (2021)) or market power among sellers (as in Bruno and Sexton (2020)), either of which could cause the price to be relatively constant independent of the amount of market activity. This finding suggests that farmers do experience an increase in the shadow value of their right, but it is primarily through the possibility of sale in an active market as opposed to an increase in the market price.

an F statistic of 2.

[13] The standard deviation of restrictions is 0.40, implying that the percent change in transaction volume for a 1 s.d. change in restrictions is $0.40 \times 160.61/104.74 \times 100 = 61.3\%$.

[14] Imputing an average price of zero for conservancies with no transactions does not change this result (results not shown).

6.2 Effect of water prices on agricultural outcomes

To measure substitution towards capital–intensive irrigation, I look for effects on the use of efficient and capital–intensive irrigation methods, here characterized by micro–sprinklers and drip irrigation, versus "inefficient" methods of flooding, sprinklers and canals. Table 5 shows the effect of any restriction (the sum of ground and water restrictions) on these outcomes, for both the IV specification and the baseline two-way fixed effects model.

The two-way fixed effects estimates differ substantially from the instrumented estimates in both magnitude and in some cases sign, suggesting that the TWFE estimates may be severely biased; therefore I omit results from this specification from the rest of the results. The instrument is relevant with a first stage F statistic of 52.33. Though imprecise, the IV estimates indicate that there may have been an increase in the share of land irrigated with efficient methods that comes at an almost proportional decrease in the share irrigated with inefficient methods. Taking this point estimate at face value, a one standard deviation in the area under restriction is responsible for increasing the share of land under efficient irrigation by 11.5%. On the extensive margin I also fail to detect statistically significant effects on the total land under different irrigation methods, though the relative magnitude of effects is in line with the proportional changes.

These point estimates support the idea that farms substitute towards capital in the production of irrigation, suggesting that capital and water are sufficiently substitutable in production ($\frac{\partial K^*}{\partial \lambda_m} > 0$. The imprecision of the estimates is at least partially due to the low number of observations and the aggregate nature of the data. However, it may also be a result of treatment effect heterogeneity; as discussed in the exposition of the model, perhaps only farms with access to credit or other advantages ($\rho \to 1$) are able to make capital investments, whereas smaller, less sophisticated farms contract production.

I test for this effect by estimating the effect of restrictions on metrics of firm size and sophistication. Table 6 reports the results of IV estimation of the effect of restrictions on the total extent of fruit production, average plot size, number of employees per farm, and

Table 5: Effect of restrictions on irrigation methods

	Percent			Total Hectares		
	Not irrig.	Inefficient	Efficient	Not irrig.	Inefficient	Efficient
IV	-0.010	-0.191	0.199	13.491	114.052	336.376
	(0.129)	(0.173)	(0.170)	(19.193)	(73.844)	(210.987)
TWFE	0.013	-0.013	-0.006	4.923*	78.182*	180.152*
	(0.012)	(0.024)	(0.026)	(2.547)	(41.534)	(94.263)
N	1,062	1,062	1,062	1,062	1,062	1,062
Mean Y	0.06	0.25	0.69	6.51	149.63	228.70
1st stage F	52.33	52.33	52.33	52.33	52.33	52.33

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. The idependent variable in both rows is the share of the municipality under either a ground or surface water restriction. "Inefficient" is irrigation via ditch/canal, traditional sprinklers and flooding; "Efficient" is defined as drip and micro–sprinklers. All estimates include municipality and year fixed effects, and control for total annual precipitation and the share of days with a temperature reading over 30°C in the year. Temperature and precipitation readings are aggregated to the comuna–year level by calculating the weighted average over all monitors within 150 kilometers of the municipality centroid, where weights are determined by the inverse distance of the monitor to the centroid. IV estimates use as an instrument the same precipitation and temperature variables lagged 5 years. Standard errors clustered at the municipality level.

the share of cultivated land dedicated to exports. The total extent of fruit production serves as a test for a farm exit effect, and the rest of the outcomes are rough proxies of farm size and sophistication.[15] The estimate on total fruit production is statistically insignificant and the point estimate is small compared to the outcome's mean (4%), indicating that there is little evidence of a change in the total area under production. This may reflect the fact that there was little farm exit, or that the land of farms that exited was transferred to other producers. Indeed, the rest of the results taken together are suggestive of the latter explanation; restricted areas cause municipalities to have larger plots on average, fewer employees per farm and farms that are much more likely to export. These results can only be taken as suggestive given the large amount of statistical uncertainty, but they provide some hints that the cap–and–trade system for water in Chile has had the effect of consolidating the sector dependent on the resource. This effect has also been observed in other cap–and–trade markets such as fisheries (OECD, 2017; Colby, 2000).

Finally, an important potential channel of adaptation is through crop switching. Given the single–crossing property assumption, the model predicts that farms may substitute towards crops that are less water–intensive but similar in value to their previous choice. Table 7 reports changes in the land dedicated to table grapes, avocados, and nuts, three high–value crops of varying water intensity, where avocados are the most water–intensive followed by tables grapes and lastly nuts. In terms of total acreage, the IV estimation reports a positive effect on the extent of table grape and nut production at the expense of a decrease in the extent of avocado production. This provides evidence that farmers substituted away from water intensive avocados towards other high–value fruits of lower water intensity. Nuts, which have even lower water demand than table grapes, have the only statistically significant change in area, with a one standard deviation in restricted area associated with a near doubling of

[15] The characterizations based on size and capital intensity are motivated by Foster and Rosenzweig (2022) and Helfand and Taylor (2021) and the literature on farm size and agricultural productivity. This relationship may be weaker in a more advanced agricultural context as is the case of fruit production in Chile. Exporting farms may be more profitable because of the need to overcome barriers to entry such as being able to ensure zoosanitary standards, certification, and achieving a size sufficient to supply international buyers.

Table 6: Effect of restrictions on production outcomes

	Total ha. in prod.	Avg. plot size	Empl./farm	% exporting
IV	58.521	3.143	-28.823	0.959**
	(259.140)	(3.027)	(44.327)	(0.415)
N	852	852	477	477
Mean Y	1,259.79	3.79	26.41	0.41
1st stage F	52.33	52.33	9.20	9.20

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. The idependent variable in both rows is the share of the municipality under either a ground or surface water restriction. "Total ha. in production" is the total land under fruit and nut cultivation in the municipality. "Avg. plot size" measures the average area in hectares of a plot; plots are not necessarily colinear with farms, as plots are defined as a contiguous geographic area planted by a single fruit, and a farm may involve several plots. However I cannot distinguish between the two in my data. "Empl./farm" is the number of employees per farm. "% exporting" is the percent of farms that report exports. All estimates include municipality and year fixed effects, and control for total annual precipitation and the share of days with a temperature reading over 30°C in the year. Temperature and precipitation readings are aggregated to the comuna–year level by calculating the weighted average over all monitors within 150 kilometers of the municipality centroid, where weights are determined by the inverse distance of the monitor to the centroid. IV estimates use as an instrument the same precipitation and temperature variables lagged 5 years. Standard errors clustered at the municipality level.

Table 7: Effect of restrictions on crop outcomes

	Table grapes		Avocados		Nuts	
	Total Ha	Pct.	Total Ha	Pct.	Total Ha	Pct.
IV	179.120	0.017	-28.121	-0.035	99.153*	-0.132
	(110.408)	(0.031)	(51.294)	(0.026)	(56.243)	(0.139)
N	852	852	852	852	852	852
Mean Y	45.78	0.10	41.60	0.08	35.22	0.16
1st stage F	52.33	52.33	52.33	52.33	52.33	52.33

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. The idependent variable in both rows is the share of the municipality under either a ground or surface water restriction. Pct. columns report the percent of fruit cultivated area dedicated to the fruit in question. All estimates include municipality and year fixed effects, and control for total annual precipitation and the share of days with a temperature reading over 30°C in the year. Temperature and precipitation readings are aggregated to the comuna–year level by calculating the weighted average over all monitors within 150 kilometers of the municipality centroid, where weights are determined by the inverse distance of the monitor to the centroid. IV estimates use as an instrument the same precipitation and temperature variables lagged 5 years. Standard errors clustered at the municipality level.

the average area dedicated to nuts where these are cultivated.[16] These results provide some suggestive evidence that water markets can help alleviate market distortions that weaken the relationship between comparative advantage in water and crop specialization in agriculture (Debaere, 2014).

Taken together, these results suggest that the primary channel of adaptation in response to higher market prices for water is to substitute towards high value crops of lower water intensity. I find noisy but positive effects of water marketization on adoption of precision irrigation technologies, and some weak evidence that higher market prices can lead to consolidation of the market into larger farms with more employees.

7 Robustness

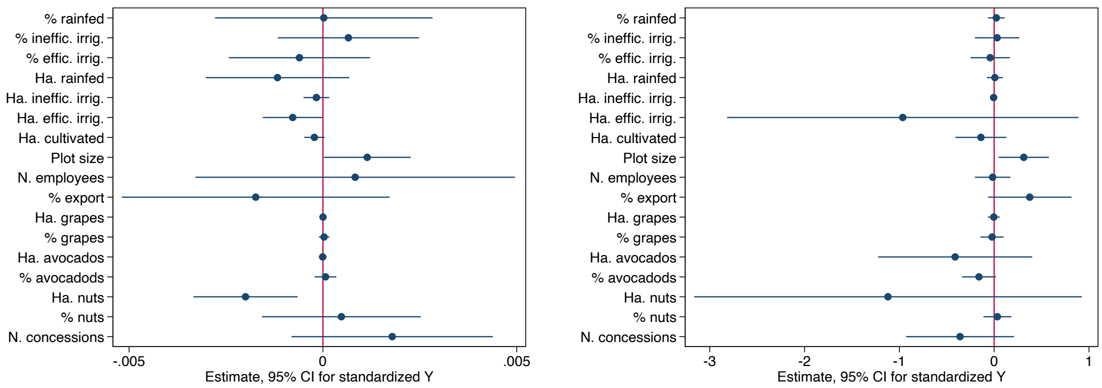
7.1 Learning from past shocks

The primary threat to the exogeneity of lagged precipitation as an instrument for restrictions is that farmers may learn from and respond to past precipitation events, and that this continues to influence their production decisions in the future. For example, if farmers are Baysian updaters, then farms who have experienced past drought conditions may be less willing to sell their water rights, which could affect the outcomes analyzed in this paper. Alternatively, suppose that farms respond to periods of water scarcity by implementing adaptive measures such as drip irrigation that remain after the shock. Then even conditional on contemporaneous precipitation shocks, areas with high previous exposure to water scarcity could have different production outcomes than those with low exposure. One way this could manifest is if farms use past precipitation shocks to anticipate restricted status, and attempt to hoard water concessions.

I test for this family of violations of the exclusion restriction by estimating a reduced

[16] The average acreage dedicated to nut production in municipalities with non–zero nut acreage is 47.2 hectares.

Figure 3: The effect of past weather shocks on outcomes in unrestricted areas



(a) Lagged precipitation (b) Lagged days above 30°C

Notes: Each point is the estimate of the coefficient on 5–year lagged precipitation (Panel (a)) or 5–year lagged days over 30°C (Panel (b)) from a regression of the outcome listed on the left hand side of the graph on precipitation and days over 30°C in t and $t-5$, plus municipal and year fixed effects. All outcomes are standardized by subtracting the mean and standard deviation, so that the X axis is in units of standard deviations of the outcome variable. Standard errors clustered at the municipal level.

form regression of outcomes directly on the instruments and controls for a subsample of municipalities that never have restricted areas declared in my sample. Given that this group of municipalities have no variation in the restrictions, if the exclusion restriction holds then the instrument should have no effect on outcomes.

Figure 3 plots the coefficients on each of the instruments and their 95% confidence interval from regressions on each of the different outcome variables. Panel (a) plots the coefficient on lagged precipitation. Encouragingly, the estimates are exceedingly precise, and even the widest confidence intervals are less than 0.005 standard deviations wide. Panel (b) plots the coefficients on days above 30°C. These estimates are less precise, but again almost all are statistically insignificant at the 5% level and most of the point estimates are less than 1/4 of a standard deviation. There are two glaring exceptions to this: though extremely noisy and insignificant, the point estimates for the extent of efficiently irrigated cultivation and the extent of nut production are about a standard deviation in magnitude. It is puzzling that these coefficients are negative, indicating that past heat shocks are associated with a smaller extent of efficiently irrigated land and of land dedicated to nut production.

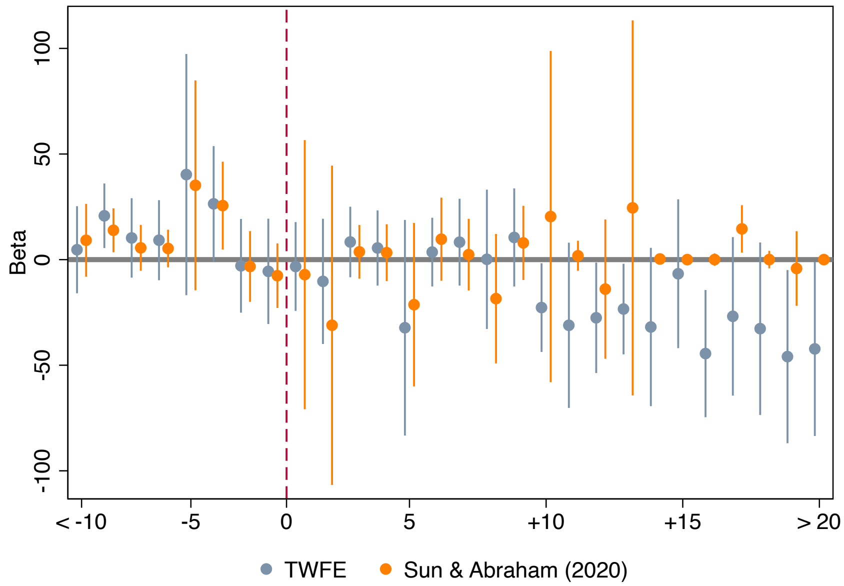
7.2 Anticipation

Another concern arises if producers are able to anticipate restrictions, which would give them an incentive to hoard water rights for their posterior market value. Even in the instrumented estimates, anticipation might be correlated with previous precipitation and temperature. After the 2005 reform which required concessions requests to justify use, there is likely limited scope for obtaining unproductive water. Even if one can convince the courts that they have a justified use, they need to demonstrate that use by proving they have infrastructure for accessing that water (i.e., by installing canals or pipes for surface water and wells and pumps for groundwater), which is a costly investment. In general it not clear how this type of anticipatory behavior would affect outcomes; if farmers use this extra water wastefully and invest in more effective technology post–restriction, this would bias my estimates of adaptation upwards. However, if farmers anticipate restrictions and adjust their behavior before markets are activated, then this would bias my estimates towards zero, as the margin of adaptation would have been exploited before the increase in the restricted area.

Figure 4 plots event study coefficients estimated from a regression similar to Equation (9), but with restriction defined as an indicator of any restriction being present in a municipality, and a coefficient estimated for each event time excluding zero. I estimate both a traditional event study specification and the Sun and Abraham (2021) estimator, given that my setting involves staggered treatment and likely treatment heterogeneity. The outcome is the number of concessions solicited. If users anticipate restriction, we would expect to see an increase in rights concessions leading up to the first restriction. This is a rather weak test, as the first restriction in a municipality may not be very large and is probably the least predictable restriction.

There is not a strong "ramping up" of rights concessions before restriction here, though a couple years before restriction there does seem to be a bump in requests indicating that users may be able to predict future restrictions. Additionally, it is plausible that concessions could increase after the first restriction if users take a nearby declaration as a signal that

Figure 4: Concessions requests relative to the first restrictions



Notes: Reference period of zero was omitted from estimation. Standard errors clustered at the municipality level.

more restrictions may come; this does not seem likely as concessions seem flat or may even decrease after the first restriction.

7.3 Alternative samples

We may have reason to believe that municipalities where no restrictions are in place in the entire sample are fundamentally different from those who are eventually "treated", either because they are not as active or valuable of agricultural areas or they have different trends in terms of production. Tables A.2, A.3 and A.4 in the appendix replicate all the main results excluding these never treated municipalities. Results are quantitatively similar, despite the fact that the number of observations falls by almost half.

8 Conclusion

In many parts of the world, moving towards market–based regulatory instruments for managing water will be a radical departure from current open–access, rationed or riparian regimes. This paper attempts to empirically estimate how farms respond and adapt to marketization for water by exploiting variation within a single regime in how active water markets are across time and space.

While this study is limited in its ability to provide precise causal estimates of the effect of marketization on agricultural outcomes, some interesting patterns emerged from the data that are suggestive of the channels of adaptation most likely to be pursued by farmers. I find some evidence that farms are induced to invest in efficient irrigation technology, and statistically stronger evidence that they do respond by switching to crops with lower water intensity of production such as nuts and table grapes over avocados. Some preliminary work has begun to study the effect of distortionary agricultural policies on water use around the world[17], and this study provides microeconomic evidence that more efficient water policies may shift the spatial production of certain crops.

I also find that restrictions induce an increase in water trading but not in average water prices, a puzzling finding that raises more questions about how prices are set in these markets. Understanding the determinants of market prices for water is outside the scope of this paper, but future work should explore the role of market power or demand elasticities in determining equilibrium prices in this setting.

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[17] See the manuscript "The global water footprint of distortionary agricultural policy" by Tamma Carleon, for example.

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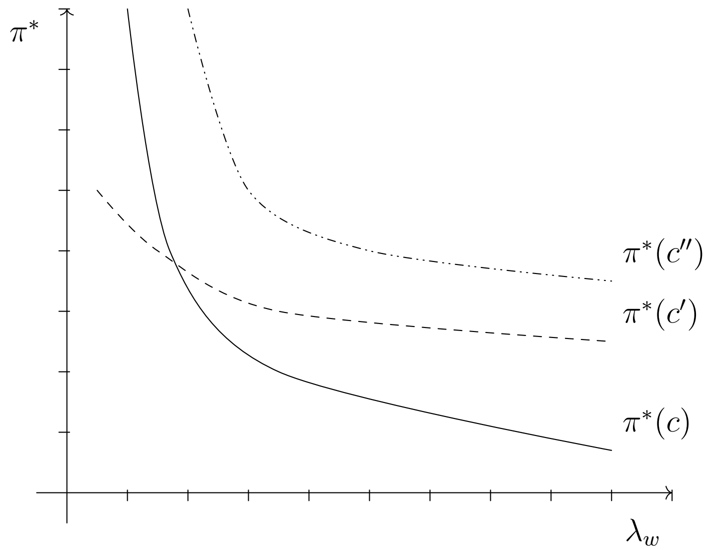
A Online Appendix

A.1 Tables and Figures referenced in text

Figure A.1: Single–crossing property in water demand



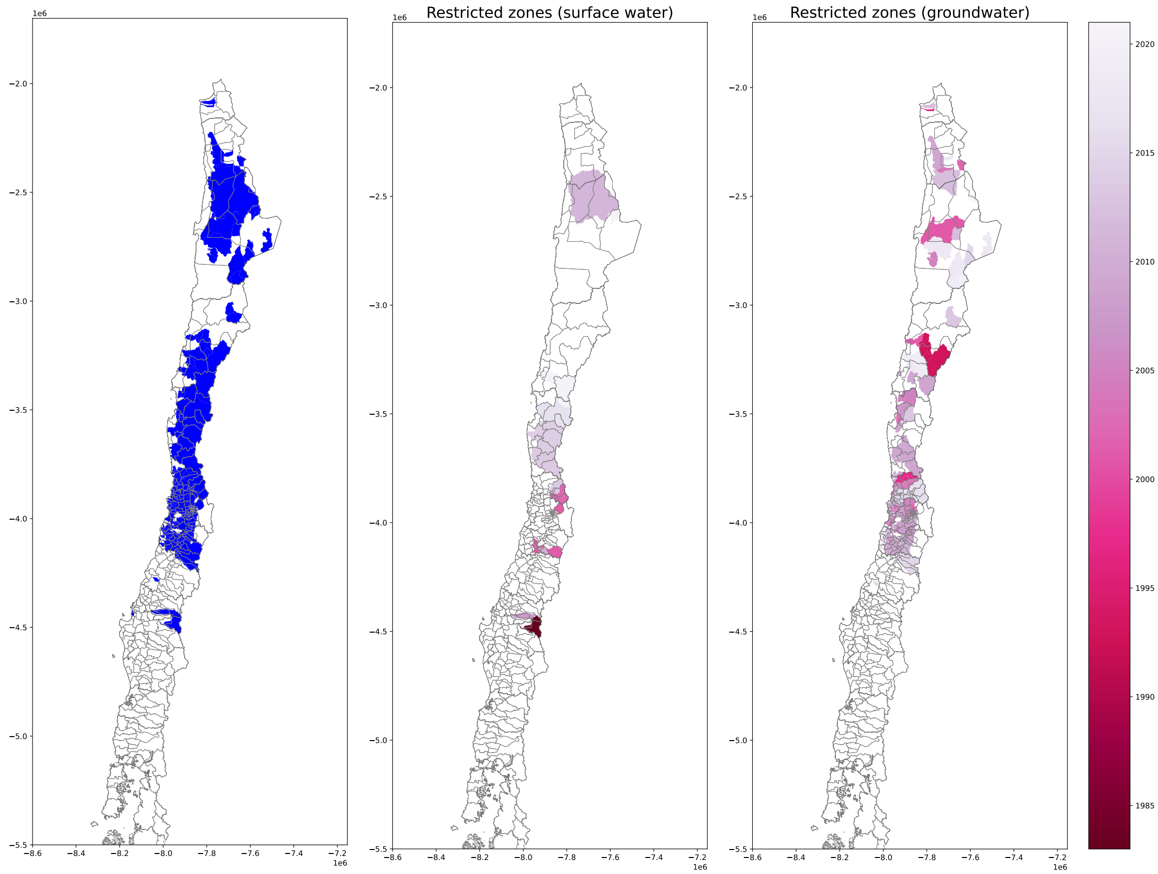
Notes: The x axis is the level of shadow prices. The y axis represents the maximized profit for crop c, $\pi^*(c)$. The "single crossing property" implies that optimal profit lines can cross at most once.

Table A.1: Units in the data

	Total no.	Mean area (km2)	Stdev. area
Watersheds	139	6,400.91	8,634.01
Sub-watersheds	489	3,365.94	4,536.16
Aquifers	536	740.50	1,337.29
Restricted groundwater sources	184	772.59	1,494.62
Restricted surface water sources	15	5,963.36	8,745.39
Comunas	346	3,774.64	9,980.31
Comunas with a resticted groundwater source	172	255.13	811.72
Comunas with a restricted surface water source	79	950.25	2,352.05

Notes: The mean area and standard deviation of the *Comunas with a restricted area* rows are calculated over the area of the comuna that overlaps (intersects) with the type of restricted area.

Figure A.2: Restricted areas over time



(a) All restrictions, 2020 (b) Surface water (c) Groundwater

Notes: The regions of Magallanes and Aysén are excluded from both maps.

Table A.2: Effect of restrictions on irrigation methods, excluding never treated

	Percent			Total Hectares		
	Not irrig.	Inefficient	Efficient	Not irrig.	Inefficient	Efficient
IV	0.029	-0.088	0.060	9.431	57.609	231.832
	(0.030)	(0.084)	(0.078)	(6.283)	(91.142)	(220.964)
N	416	416	416	416	416	416
Mean Y	0.06	0.25	0.69	6.51	149.63	228.70
1st stage F	28.81	28.81	28.81	28.81	28.81	28.81

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. "Inefficient" includes irrigation via ditch/canal, traditional sprinklers and flooding; "Efficient" includes drip and micro–sprinklers. Standard errors clustered at the comuna level.

Table A.3: Effect of restrictions on production, excluding never treated

	Total ha. in prod.	Avg. plot size	Empl./farm	% exporting
IV	-107.171	4.326*	-4.589	0.462
	(262.232)	(2.533)	(36.354)	(0.300)
N	416	416	286	286
Mean Y	1,259.79	3.79	26.41	0.41
1st stage F	28.81	28.81	12.58	12.58

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. "Inefficient" includes irrigation via ditch/canal, traditional sprinklers and flooding; "Efficient" includes drip and micro–sprinklers. Standard errors clustered at the comuna level.

Table A.4: Effect of restrictions on crop choice, excluding never treated

	Table grapes		Avocados		Nuts	
	Total Ha	Pct.	Total Ha	Pct.	Total Ha	Pct.
IV	155.504	-0.028	-44.793	-0.022	107.880**	0.005
	(98.615)	(0.027)	(71.437)	(0.027)	(54.079)	(0.062)
N	416	416	416	416	416	416
Mean Y	45.78	0.10	41.60	0.08	35.22	0.16
1st stage F	28.81	28.81	28.81	28.81	28.81	28.81

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. "Inefficient" includes irrigation via ditch/canal, traditional sprinklers and flooding; "Efficient" includes drip and micro–sprinklers. Standard errors clustered at the comuna level.