Water Market Dynamics in the Presence of Environmental Variability

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December 2019

PRELIMINARY DRAFT

Abstract

The challenges associated with effectively managing water resources are highly salient in arid regions of the world. Water markets have been promoted as an efficient solution, and the foundational requirement for such an approach – a system of comparatively well-defined, tradable property rights – has emerged in some particularly water-stressed areas. Yet, comprehensive, data-driven empirical assessments of water markets' effectiveness in promoting timely reallocation remain scarce. In this paper, we explore whether environmental shocks spur market transactions and also study how public subsidies play a role in these dynamics. We compile a unique dataset that accounts for all recorded water right transactions, all subsidies for water use efficiency, as well as precipitation and temperature patterns in Chile from 1979 to present. Our panel dataset enables estimation of the impacts of both persistent environmental shocks (i.e., droughts) and government subsidies at sub-national scale. We provide evidence on water market performance in the face of environmental variability, as well as the nation-wide effects of government subsidies for irrigation technology on exchange.

JEL Codes: D23, P14, P48, Q15, Q25, Q28

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1 Introduction

The promise of market-based mechanisms for addressing challenging environmental and natural resource problems has been a focus of economists for many decades (Coase, 1960; Stavins, 2011). In theory, these mechanisms ought to encourage efficient outcomes by aligning incentives for conservation and reallocation, as well as providing opportunities for low-cost negotiation to resolve competing resource demands. We contribute to this literature by exploring whether persistent environmental shocks spur additional water market transactions that could help to redistribute the resource. We also study how public infrastructure subsidies play a role in these dynamics. Despite predictions of efficient market allocation, transaction costs and other barriers to trading water often hamper exchange and render markets less effective. A better understanding of these obstacles is of interest both academically and for policy applications. In particular, it has important implications for how well suited market approaches may be for climate change adaptation. In addition, we provide insight into how investment subsidies for asset-specific complementary capital affect the dynamics of markets for renewable resources.

Surface water and groundwater, as common-pool resources, may suffer from inefficiently high levels of extraction in the absence of well-designed management and coordinating institutions (Ostrom, 1990). The challenges associated with effectively managing water resources are already highly salient in arid regions of the world. Against this backdrop, changing climatic regimes are expected to increase water scarcity and stress by reducing availability, increasing variability, changing the timing of flows and recharge, and potentially increasing demand, especially for irrigation purposes (Vörösmarty et al., 2000; Covich, 2009; McDonald et al., 2011; Tack, Barkley and Hendricks, 2017). Accordingly, as scarcity increases, the development of social institutions that can encourage timely, sensible reallocation of water across locations and uses will become more important.

Economists have proposed markets as a solution for many common-pool resource problems, and as an important element of adapting to climate change (Anderson and Libecap, 2014; Anderson et al., 2018). Water is no exception, with markets having been pursued as a key component of management strategies in Chile, Australia, and many states in the Western U.S., among other places (Grafton et al., 2011; Rey et al., 2019). As water becomes scarcer within a given river basin, price signals generated by the market for extraction rights are expected to prompt both reallocation and intelligent investment decisions in water-related capital and infrastructure. Providing a better understanding of the performance of this approach in the face of environmental variability is a key goal of this paper.

The advantage of any market-based institutional regime depends in large part on how easily resource use can be rearranged to realize allocative efficiency gains. This includes the ability to identify high-valued uses at any given point in time as well as service new demands as they emerge throughout time. In short, markets are most effective when transaction costs are relatively low. Experiences to date with water markets have been mixed, in part due to costly barriers arising from measurement difficulties, regulatory restrictions, and political economy pressures. Developing tools to reduce these transaction costs has become an important task for improving market function in particular and adaptive capacity more generally (Grafton et al., 2011; Leonard, Costello and Libecap, 2019).

In this paper, we focus our analysis on one of the few water markets that has been implemented at national scale: Chile's. Chile has maintained a formalized system of tradable property rights to water since 1981. At that time, the rights of private appropriators to both divert water for consumptive use and also trade these rights were affirmed. Since then, debate and controversy has emerged regarding how effective the resulting market has been in reallocating water use, with increasing recognition that the market has historically been hampered by consequential transaction costs (Bauer, 2004, 2014). For example, recent studies have documented significant costs of regulatory trading restrictions (Edwards et al., 2018). As a result, new attempts to understand market dynamics in Chile can not only help to improve domestic water allocation but also provide insights for better institutional design elsewhere. In particular, Chile is a good candidate because it presents both areas of reliable abundance as well as regular scarcity under the same institutional framework.

To achieve these goals, we compile a unique dataset that accounts for all recorded water right transactions, all subsidies for water use efficiency, as well as precipitation and temperature patterns in Chile from 1979 to present. Our panel dataset enables estimation of the impacts of both persistent environmental shocks (i.e., droughts) and government subsidies for irrigation efficiency improvements. We find that persistent drought is associated with an increase in trading for both surface and groundwater rights, suggesting that the market has, overall, provided opportunities for adaptation. Furthermore, government subsidies appear to play a statistically significant, if small, role in spurring trading: a 10% increase in year-on-year subsidy disbursements is associated with a 0.6-0.7% increase in transactions. However, additional analysis suggests the effects are much larger when subsidies are directed to small-scale users who may face greater barriers to trading due to credit constraints and missing infrastructure.

The remainder of the paper is structured as follows: Section 2 provides a discussion of transaction costs in water markets, as well as background on the Chilean water market and its development. Section 3 provides a theoretical framework for the problem. Section 4 introduces our data sources. How we employ these data for econometric estimation is described in Section 5. Section 6 summarizes our preliminary results. Section 7 places the results in context and discusses paths forward.

2 Background

2.1 Chile's Water Market Development

The institutional rules governing water in Chile have long recognized private claims to the resource, despite shifts throughout time in the strength of legal protections. In 1967, reforms granted the government substantial control over water resources, but these were overturned in 1981 during Pinochet's rule (Bauer, 2004). The reform claimed water to be a "national good for public use," but affirmed private property rights to water (Donoso, 2015). The 1981 law also unbundled water rights from land tenure and use. This allowed irrigators to trade water used in relatively low-value applications away from their own properties and greatly expanded the scope for markets—thus began the modern era of water marketing in Chile.

Additional reforms in 2005 granted the Dirección General de Aguas (DGA) additional authority to define volumetric claims, levy fees on unused water rights, and impose ecological flow mandates when new water rights are registered in basins with unclaimed flows (Edwards et al., 2018). Nonetheless, the registration of private claims and recording of transactions of those rights remain inconsistent, and the DGA has not successfully adjudicated all claims in many watersheds (Lajaunie et al., 2011). Especially groundwater rights lag in terms of quantification and formalization. This lack of institutionalization has been attributed to the presence of high transaction costs due to uncoordinated stakeholders and a lack of conveyance infrastructure (Hearne and Donoso, 2014).

During the lifetime of tradable water rights in Chile, debate has arisen regarding how effective the water market really is in enabling flexible reallocation. As Bauer (2014) notes, initial enthusiasm for the Chilean water market in the 80s and 90s was tempered by later realization that the level of clarity in rights definition (i.e., volumetric certainty, legal security, and clear expectations of how third-party impacts would be handled) that would enable low-cost, routine transactions was not present. Nonetheless, other voices argue that the Chilean water market is broadly meeting needs and reallocating use reasonably well despite a lack of regular large-scale water transfers (Hearne and Donoso, 2014).

Meanwhile, Chile introduced a subsidy program for irrigation system efficiency improvements in the mid-1980s. The stated goal was to encourage prosperous agriculture by increasing water use productivity. By some accounts, the policy has proved nominally successful: growth in the agricultural sector has outpaced that of the rest of the economy in recent decades (Hearne and Donoso, 2014). One constraint of this subsidy program is that it can only benefit natural and legal persons that hold property rights. Proposed infrastructure investments are evaluated on a case-by-case basis, and if approved, a given fraction of the total cost is covered with public funds. Importantly, this policy influences water market outcomes by increasing water efficiency and developing key conveyance infrastructure. What impact these subsidies might have on the market in practice will depend on the existing level and scope of transaction costs.

2.2 Transaction Costs in Water Markets

Ample opportunities arise for technical, social, and regulatory issues to hamper trade in water. Some of these are usefully summarized by Leonard, Costello and Libecap (2019) in the context of the western United States. These costs include in large part the barriers that regulatory agencies impose to address external impacts of transfers, the costs of defining rights and assessing such external impacts (e.g., measurement), conveyance constraints, and pressure from those who suffer negative pecuniary impacts. These barriers arise in other countries as well, and a representative but not exhaustive list of general sources of transaction costs includes:

- **Measurement requirements**: Where rights are defined to diversions (which is typically the case), a trade may require estimation of existing consumptive uses of water (e.g., crop evapotranspiration) to assess whether downstream users will be harmed by a proposed transfer. In basins where a detailed adjudication of water use and entitlements has not already been undertaken, this imposes costs on exchange parties.
- **Conveyance constraints**: Marketing suface water typically requires ensuring delivery to the new user. This might entail either changing a point of diversion within a given physical system or moving water out of one system to another. In either case, a suitable conveyance network may not exist, may suffer from capacity constraints, or—even where infrastructure exists and has capacity—may be subject to market power on the part of the conveyance owner. This necessarily imposes sometimes significant costs that may render trades uneconomical.
- **Intersectoral differences**: Much interest in water markets concerns transfers from relatively low-value agricultural uses to municipal or industrial uses. Costs described in the preceding two bullet points apply especially to such transfers: While agriculture-to-agriculture trades may entail external costs (e.g., if a transfer entails reduced flow in shared distribution infrastructure), the scope and scale of these may be larger in intersectoral, inter-basin trades and require more effort to demonstrate or avoid. Furthermore, these distinct

use types are often not located near one another, increasing the need for costly conveyance.

• **Security of rights**: In some cases water rights are subject to use restrictions (e.g., that water must be put to "beneficial use" in the western US) or perhaps even subject to risk of government expropriation. For example, a beneficial use restriction may cause water that is freed up due to irrigation efficiency improvements to be viewed as having been "wasted" or used non-beneficially prior to its sale, potentially rendering rights to that water volume void (Bretsen and Hill, 2008). Insofar as these uncertainties reduce the expected net gains from acquiring or attempting to sell rights, exchange is less likely to occur.

• **Political economy pressures**: Opposition to water trades often arises from local communities that do not hold water rights yet are nonetheless believed to rely on agricultural production for their economic well-being. Where water trades entail a reduction in irrigated acreage, external parties may exert political influence to block such transfers. Just as policies to mitigate greenhouse gas emissions often elicit opposition from coal-dependent communities (in addition to extractive industries themselves), water markets suffer from similar local political economy obstacles.

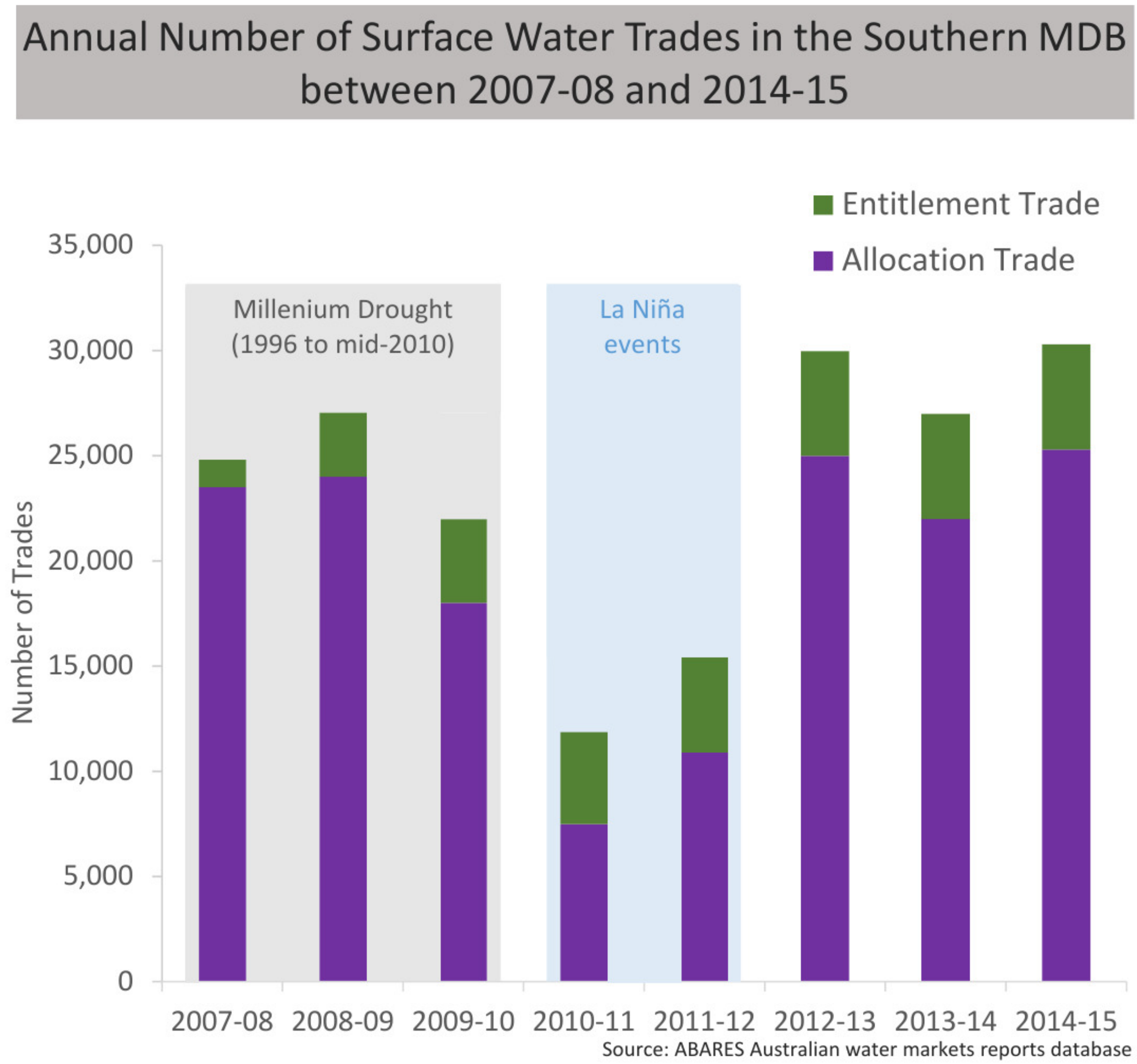
Our primary focus is to consider how these transaction costs may inhibit trading in response to variation in environmental conditions. When a drought restricts supply or high temperatures induce additional consumptive water demand, an efficient allocation will see some low-value uses that were undertaken during relative abundance curtailed or given up altogether. If this is accomplished through market mechanisms, trade volumes could increase.

Evidence for such responses in other water markets around the world is mixed. Two examples, the Murray-Darling Basin market in Australia and California's water market, showcase this disparity. Figures 1 and 2 present time series of recent trading volumes in these markets. From 1996 to mid-2010 Australia experienced what is now called the "Millenium Drought," a long-term persistent dearth of rainfall that stressed agricultural communities as well as municipal drinking water suppliers. Nonetheless, trading volumes were relatively high compared to those during subsequent La Niña events, especially for annual allocations.[1] Evidence suggests that the market was broadly successful in reallocating water for short- and medium-term needs (Hughes, Gupta and Rathakumar, 2016).

Thereafter, California experienced a similar, if somewhat shorter, drought from 2012 through 2015; in contrast to the Australian experience, observed volume of water traded did not increase (if anything, it appears to have declined). While it is likely that informal trading helped to reduce the costs of addressing scarcity within agricultural irrigation dis-

[1]In the Murray-Darling, entitlements represent claims to water in perpetuity, the actual volume of which that is available in any given year being administratively determined according to pre-determined rules. Available volumes are known as allocations.

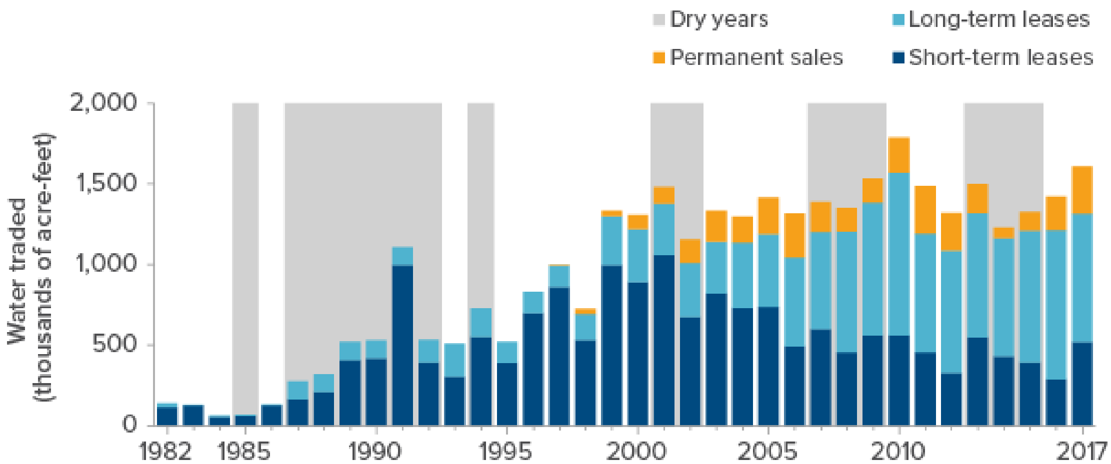
Figure 1: Murray-Darling Trades



NOTES: Sourced from ABARES transactions database.

tricts, intersectoral trades were few. This has many causes, including constraints due to limited conveyance infrastructure (Regnacq, Dinar and Hanak, 2016). A salient example of a regulatory barrier to trading is state water conservation mandates that water utilities faced during this period. The State of California imposed administrative water conservation targets, relative to a pre-drought baseline, on major municipal water purveyors. While it is not the case that all mandated conservation could be cost-effectively substituted through market transactions, trading with agriculture, or even between municipalities, may have reduced some of the hundreds of millions in losses suffered by utility ratepayers (Nemati, Buck and Sunding, 2018). More broadly, recent trading volume in California's market appears to be largely insensitive to the drought conditions, as documented by Hanak and Stryjewski (2012).

Figure 2: California Trades



NOTES: Sourced from (Hanak and Stryjewski, 2012).

In Chile, transaction costs and other restrictions that inhibit trading have been documented as well. The national DGA has authority to restrict water transfers to achieve some political objectives, and these interventions may inhibit both cost-effective permanent reallocation and adaptation to temporary drought. One salient example is the determination by regulators that agricultural rights purchased on the market in northern Chile may not be used for mining activities; the motivation is the protection of indigenous agricultural uses and riparian ecosystems. These restrictions may deliver net benefits if environmental or indigenous uses have large spillovers and coordination among beneficiaries is costly. However, the northern reaches of Chile are the most arid in the country and where the most high-valued uses of water can be found (Hearne and Donoso, 2014). As a result, the costs of misallocation are very high. In lieu of a market remedy, mining firms have invested in costly desalination. The costs of these restrictions have been estimated in the tens of millions of dollars per year (Edwards, Cristi and Díaz, 2012; Edwards et al., 2018). In addition to regulatory constraints, administrative capacity shortfalls have historically limited the government's ability to accurately define claims and enforce rights, which also reduces incentives to trade. In particular, this could result both in a diminution of perceived security as well as a need to undertake costly measurement procedures when attempting to market water. Indeed, resolving conflict over volumetric entitlements in Chile has historically often involved costly private litigation (Grafton et al., 2011). We assess whether—under such conditions—Chilean water markets appear broadly capable of responding to changing environmental conditions.

In addition, we ask whether the subsidy program described in 2.1 has had an effect on traded volume; to do so, we also estimate the relationship between these subsidies and traded water volumes. Scholars have noted that irrigation efficiency improvements may free up water for application elsewhere (demand reduction), encourage intensification and expansion of water use due to increased productivity, or both (Grafton et al., 2018). The former effect would increase sales from subsidized parties, while the latter could either not prompt exchange with other parties or, in extreme cases, induce purchasing where the scale of the subsidized irrigation project expands total on-farm water requirements. Furthermore, the program may have an additional effect on market behavior: where rights are not fully adjudicated and the subsidy program involves quantifying water savings, rights holders may feel more confident that their existing claims will be recognized and not imperiled should they choose to market saved water. The following section posits a theory relating availability of extraction permits and trading, and subsequent sections describe our data and empirical approach.

3 Theory

In this section we outline a simple model depicting the decision making of firms when faced with climate uncertainty that affects water availability. To account for these dynamics, we borrow the approach by Pommeret and Schubert (2018) who study emission permit dynamics in the face of uncertainty and irreversibility. Their model is amenable to the water problem because we are concerned with incentives for extracting water and investing in irrigation technology. The question of interest is how environmental variability affects individual decisions for water consumption and investment on irrigation technology.

Consider a two period competitive water market with N risk-neutral firms. Other than water reduction, assume all other production decisions as given. The cost of reducing water consumption in firm i is given by $C_i(Q_i, K_i) = c_i Q_i^{\alpha} K_i^{-\beta}$ as consumption reduction and water efficiency capital (henceforth technology), respectively. The parameters satisfy $c_i > 0$, $\beta > 0$, and $\alpha > 1 + \beta$. Conveniently, the aggregate cost function is the envelop of the individual cost functions. That is, if $Q = \sum_i Q_i$ and $K = \sum_i K_i$, then aggregate cost of water reduction is given by $C(Q, K)$. The cost function satisfies $C(0, K) = 0$, it is convex in consumption reduction, $\partial C_i/\partial Q_i > 0$, $\partial^2 C_i/\partial Q_i^2 > 0$, and concave in technology, $\partial C_i/\partial K_i < 0$, $\partial^2 C_i/\partial K_i^2 > 0$.

Pommeret and Schubert (2018) show that a single-period market clearing condition implies:

$$C(Q,K) = cQ^{\alpha}K^{-\beta} \ \text{ with } \ c = \left(\sum_i c_i^{\frac{1}{1+\beta-\alpha}}\right)^{1+\beta-\alpha} \tag{1}$$

It follows that individual consumption reduction and technology investment are given by:

$$Q_i = Q\left(\frac{c}{c_i}\right)^{\frac{1}{\alpha-(1+\beta)}} \ \text{ and } \ K_i = K\left(\frac{c}{c_i}\right)^{\frac{1}{\alpha-(1+\beta)}} \tag{2}$$

In the absence of a cap and fixing individual output, each firm extracts an unregulated set amount of water $\bar{U}_i$ both time periods. It follows that total unregulated extraction is given by $\bar{U} = \sum_i \bar{U}$. Suppose now that the regulator sets an overall cap on extraction at time t, W_t, which is then distributed to individual firms as W_{it}. For the cap to be effective, it must be that $W_t < \bar{U}$ and $W_t = \sum_i W_{it} \ \forall \ t \in \{1,2\}$. Firms are also allowed to bank permits across periods. Banking is denoted as B_{i1}, and total banking in the market is given by: $B_1 = \sum_i B_{i1}$.

At time 1, the firm knows the rights assigned, but in the next period there is a chance that its allocated extraction rights might be adjusted due to changes in the recharge of the water basin. On the one hand, the total cap could be increased to $W_1+\bar{\Delta}$, $\bar{\Delta} > 0$, with probability q. On the other hand, the total cap could be reduced to $W_1-\underline{\Delta}$, $\underline{\Delta} > 0$, with probability $1-q$. To ensure the validity of the market, the cap is always binding, $W_1 + \bar{\Delta} < \bar{U}$. It follows that each firm's extraction rights in the next period could be adjusted to $W_{i1}+\bar{\Delta}_i$ with probability q, or to $W_{i1} - \underline{\Delta}_i$ with probability $1-q$. Consequently, $\bar{\Delta} = \sum_i \bar{\Delta}_i$ and $\underline{\Delta} = \sum_i \underline{\Delta}_i$, and $\mathbb{E}_1[W_{i2}] = W_{i1} + q\bar{\Delta}_i + (1-q)\underline{\Delta}_i$. It follows that total individual intertemporal consumption changes are given by $Q_{i1}+Q_{i2} = 2(\bar{U}_i - W_{i1}) + \underline{\Delta}_i - q(\underline{\Delta}_i + \bar{\Delta}_i) = \eta_i(q)$. For a given firm, $\eta_i(q)$ could be either positive or negative, but total reduction in consumption, $\eta(q) = \sum_i \eta_i(q)$, must be strictly positive.

Firm i chooses water reduction, Q_{it}, technology levels, K_{it}, and banking, B_{i1}, so as to minimize the total discounted cost from water reduction. The unit price of technology is exogenously given by k, and the firm-level of technology investment is denoted as I_{it}. Assume further that investment is fully reversible and capital can be traded at price k. The firm takes water right prices, p_t, as given. The firms' discount factor is common and given by δ. With this setting, the Bellman equation for an initial level of technology at time 1, K_{i0}, is given by:

$$V_{i1}(K_{i0}, W_{i1})) = \min_{Q_{i1}, I_{i1}, B_{i1}} \big\{C_i(Q_{i1}, K_{i0} + I_{i1}) + kI_{i1} - p_1 \left(W_{i1} - (\bar{U}_i - Q_{i1}) - B_{1i}\right) \\ + \delta \mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2}))\right]\big\} \tag{3}$$

with

$$\mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2})\right] = qV_{i2}(K_{i1}, W_{i1} + \bar{\Delta}_i)) + (1-q)V_{i2}(K_{i1}, W_{i1} - \underline{\Delta}_i)) \tag{4}$$

This problem can be solved using standard dynamic programming (See Appendix for solutions and proofs). First, consider the case when there is no uncertainty and, at period 1, all firms know the cap in period 2. Optimal water consumption reduction, technology investment, and banking in period 1 would be given by:

$$Q^*_{i1} = \frac{\eta_i(q)}{1 + f(\delta)} \; ; \; f(\delta) = \left(\left(\frac{1-\delta}{\delta}\right)^{\beta} \frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}} \tag{5}$$

$$K^*_{i1} = \left(\frac{\beta c_i}{(1-\delta)k} Q^*_{i1}\right)^{\frac{1}{1+\beta}} \tag{6}$$

$$B^*_{i1} = \frac{(\bar{U}_i - W_{i2}) - f(\delta)(\bar{U}_i - W_{i1})}{1 + f(\delta)} \tag{7}$$

It follows that under the existence of a binding cap, first period water consumption reduction is always positive. Banking on the other hand, could be either positive or negative depending on the relationship between uncapped consumption, and caps on both periods in relation to $f(\delta)$. We denote this benchmark as the deterministic scenario, which will be the baseline to establish how the firm reacts to uncertainty. Consider now the case when firms face uncertainty over the cap in the second period. Denote this solution with a # symbol. It can be shown that optimal water consumption reduction, technology investment, and banking in period 1 would be now given by:

$$f(\delta)Q^{\#}_{i1} = \left(q \; {\underline{Q}^{\#}_{i2}}^{\frac{\alpha-(1+\beta)}{1+\beta}} + (1-q) \; {\bar{Q}^{\#}_{i2}}^{\frac{\alpha-(1+\beta)}{1+\beta}}\right)^{\frac{1+\beta}{\alpha-(1+\beta)}} \tag{8}$$

$$K^{\#}_{i1} = \left(\frac{\beta c}{(1-\delta)k} Q^{\#}_{i1}\right)^{\frac{1}{1+\beta}} \tag{9}$$

$$B^{\#}_{i1} = Q^{\#}_{i1} - (\bar{U}_i - W_{i1}) \tag{10}$$

The total effect of uncertainty, relative to the deterministic case, can be formalized as follows:

Proposition 1 *Under uncertainty over the total extraction cap in the second period, W_2, both total water consumption, Q_1, and total technology investment, I_1, increase (decrease) if and only if $\alpha > (<) 2(1 + \beta)$.*

In words, if the marginal cost of reducing water consumption is convex (concave), uncertainty encourages firms to decrease (increase) their water consumption and investment in technology. In general, firms have an incentive to invest because it reduces the marginal cost of decreasing water consumption, which is exogenously imposed by the regulator. Accordingly, there is an intrinsic tradeoff between reducing consumption across periods, and the possibility of having the allocation reduced in period 2 creates incentives for banking and investing so as to avoid an excessive increase in costs due to further limits in extraction. As the cap could become binding with some probability, total reduction in water consumption in period 1 increases. The convexity of the cost of reducing consumption then implies that the marginal value of a unit of water rights will increase accordingly, and so does the price at which water rights are transacted in the market in the initial period.

These adjustments drive two distinct effects. First, uncertainty around the future cap encourages water use efficiency through an overall reduction in consumption as well as investment in technology. Second and more importantly for this study, an increase in the value of the water permits results in low-reduction-cost firms releasing their permits to the market. This result is formalized as follows:

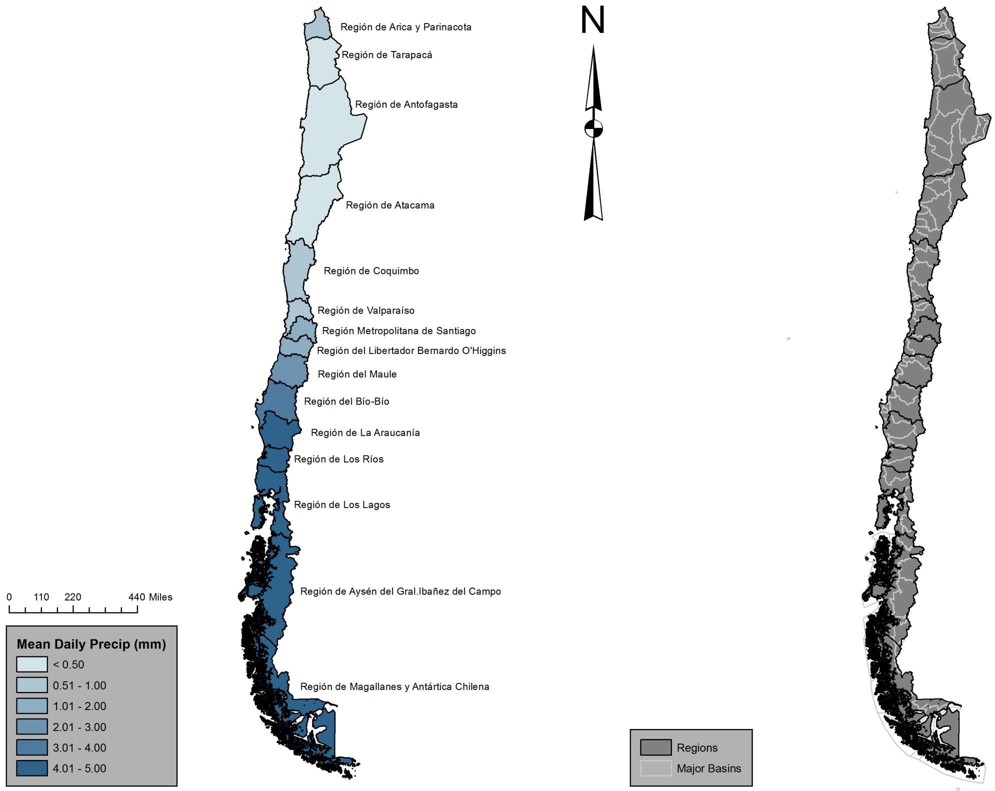
Corollary 1 *Under convex costs of water consumption reduction and uncertainty over the total extraction cap, the price of water permits increases and so does the volume of permits released in the market.*

This corollary is a particularly powerful prediction, and it lies at the core of some of the hypothesized advantages of markets for environmental resources. In the face of scarcity, markets would allocate the resource from low to high value users. Operationally, this results follows from the convexity of the cost function. Our task is now to evaluate if the prediction holds in an empirical setting. The next sections cover the data utilized, as well as our strategy to evaluate if this prediction holds in our case study.

4 Data

Our dataset is compiled from two main sources: the US National Oceanic and Atmospheric Administration (NOAA) and the Chilean DGA.

Figure 3: Chile: Precipitation & Watersheds

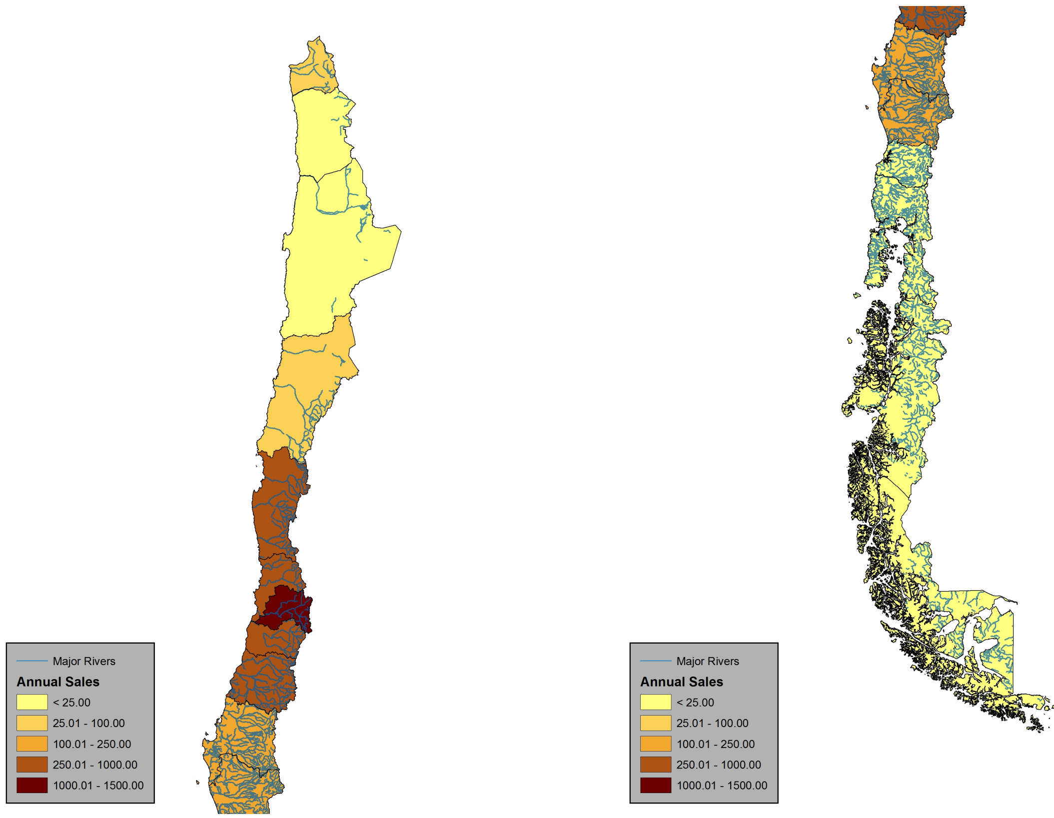


NOTES: Maps of Chile with regions outlined. Left panel shows daily precipitation mean from 1950-2019 by region, while right panel illustrates how regional boundaries sometimes span multiple watersheds.

Precipitation and temperature data are taken from NOAA's Precipitation Reconstruction over Land (PREC/L) data product. Historical daily measures are available for the time period covered by our transaction and subsidy data at 0.5 × 0.5 degree resolution. We aggregate these measures across the water year, July to June, so that our temporal units span two calendar years (e.g., water year 1979-80). The left panel of Figure 3 shows mean daily precipitation by region.

We couple these measures with DGA data containing all subsidy disbursements from 1979 to 2018 and all recorded permanent transactions to 2015. The end of the transaction data constrains the time period of our estimating sample (water year 2014-15). The transaction data include transfers of both surface water diversion and groundwater extraction rights. We restrict our attention to transfers flagged as market sales in order to omit those between family members as well as bequests. The subsidy data include project-level information on the amount of subsidy provided as well as total project costs. Recipients (both private individuals and firms) are identified by name, although this identification does not typically match registered names in the transaction database.[2] Subsidies have been disbursed regularly in all Chilean administrative regions; Figure 5 presents the logarithm of subsidy disbursements by region.

Figure 4: Chile: Rivers & Trading Frequency

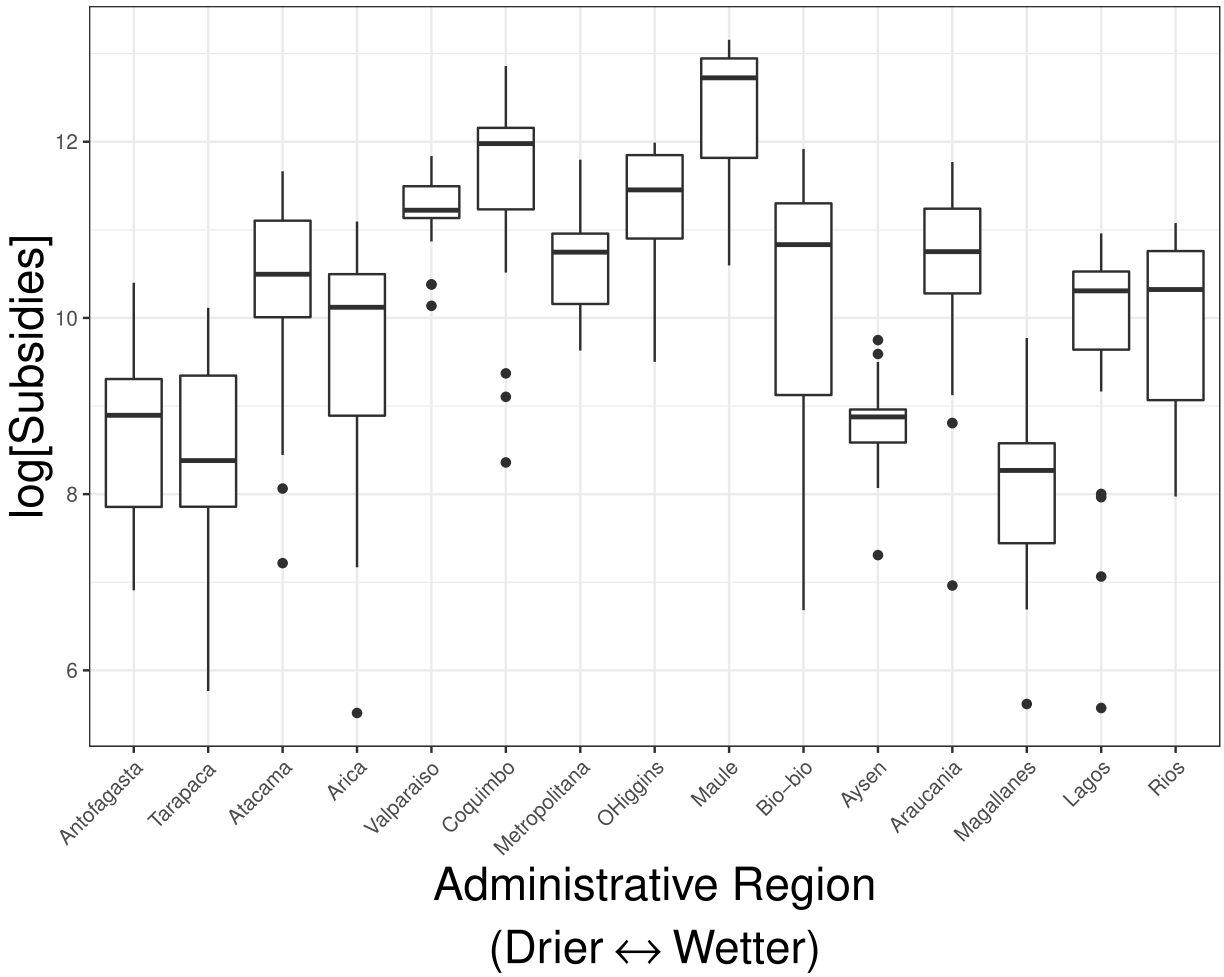


NOTES: Maps of Chile with regions outlined and colored by trading frequency (mean annual sales, 1979-80 to 2014-15). Left panel shows north part of the country, and right panel south.

Table B.1 from Appendix B.1 summarizes these measures by administrative region. We conduct our analysis using region-level cross-sectional units. Doing so necessarily introduces some aggregation bias because multiple watersheds (the spatial unit at which water rights are administered) will be treated as joint observations. The right panel of Figure 3 illustrates this overlap. We are exploring alternative measures of climate variables that are available at watershed scale.

[2] We are currently exploring opportunities to match subsidy disbursements to transaction records.

Figure 5: Subsidy Distributions by Region



NOTES: Mean, interquartile range, and 5- and 95-percentile values are shown for each Chilean region. Drier regions occupy the left side of the horizontal axis, with annual average precipitation increasing to the right.

5 Empirical strategy

This section describes our estimation strategy and econometric assumptions. To evaluate how the market responds to climate variability, we estimate several different specifications based on the following linear model:

$$\log(T_{it}) = \alpha + \beta \log(S_{it-1}) + \gamma' \mathbf{V}_{it} + \delta' [\mathbf{V}_{it} \times \log(S_{it-1})] + \theta' \mathbf{X}_{it} + \epsilon_{it} \tag{11}$$

in which T_{it} are transactions in region i in year t, S_{it-1} is the subsidy disbursement amount in the previous year, and $\mathbf{V}_{it}$ is a vector of climatic variables (i.e., precipitation and temperature). The term $\mathbf{X}_{it}$ is a vector of region and year fixed effects. The climatic variables represent, for any given year t, the 3-, 5-, or 7-year (preceding) running-average of the deviations from the long-term (1947-2019) mean, normalized by the standard deviation. These measures include deviations from annual total precipitation and mean annual temperature and are designed to capture the degree of persistent environmental deviation. We choose this measure because very short-term environmental shocks—say, a single dry year —are likely to induce adaptations in local, informal markets, perhaps even leveraging water-sharing agreements within a small water user association. These types of exchanges are typically not reported to the DGA and would not appear in our data. Our results therefore characterize the decisions to reallocate water that are based on persistent drought and/or medium- to long-term periods of high temperatures.

Identification requires that both subsidies and climate variables are uncorrelated with the error term. Naturally, only climate variables are plausibly exogenous to other determinants of individual transactions, conditional on observables. In contrast, subsidy disbursement is almost certainly not random and indeed likely to be correlated with regional and local unobservables that impact trading. This fact limits any causal interpretation of the estimates reported in the next section; nonetheless, the fixed effects approach described above will account for systematic distribution of subsidies to high-value places or years. We believe, even in the absence of a a quasi-experimental setting or instrumental variables approach, that Eq. (11) provides a strong basis for understanding how subsidy disbursement may be broadly associated with market activity.[3]

6 Results

Table 1 presents the estimation results for several variations on our estimating equation, Equation (11). Columns (1) through (6) present the effects of subsidies and individual climate variables, while columns (7) and (8) include both precipitation and temperature. Our preferred climatic measure is the 5-year running-average deviation, but Appendix B provides several replications of the analysis under different climate specifications.

The estimated relationship between lagged subsidy disbursements and trading volume is clearly sensitive to the inclusion of region-level fixed effects. Given the large variation in the distribution of regional subsidy amounts shown in Figure 5, it may be that subsidies flow to areas where markets are particularly active for unobserved reasons, e.g., agricultural production is heterogeneous. The inclusion of both region and year fixed effects allays in part these endogeneity concerns; after including those, subsidies appear to have a statistically significant if much smaller association with trading volume. The association of subsidies with

[3] We are exploring options to instrument for subsidy disbursements.

Table 1: Main Panel Estimation Results

	log[Transfers]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log[Subs]	0.07***	0.09***	0.32***	0.07***	0.28***	0.07***	0.29***	0.06***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Precip (5y)	-0.34***		0.35	-0.81***			0.33	-0.86***
	(0.08)		(0.20)	(0.16)			(0.20)	(0.16)
Temp (5y)		-0.07			-0.07	-0.31*	-0.02	-0.39**
		(0.10)			(0.15)	(0.12)	(0.15)	(0.12)
log[Subs] x 5y rain dev.			-0.01	0.07***			0.01	0.07***
			(0.02)	(0.02)			(0.02)	(0.02)
log[Subs] x 5y temp dev.					0.09***	0.04*	0.09***	0.03
					(0.02)	(0.02)	(0.02)	(0.02)
Region FE	X	X		X		X		X
Yearly FE	X	X	X	X	X	X	X	X
Observations	540	540	540	540	540	540	540	540

Robust standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

the volume of transactions is particularly robust across specifications with region fixed effects. According to these estimates, a 10% increase in the amount of subsidies toward irrigation or conveyance infrastructure is associated with an increase of about 0.6-0.7% in the number of transactions. These estimates are significant at the 1% level.

Meanwhile, the relationship between medium-term precipitation anomalies and trading volume is much clearer. As droughts intensify across years, more water is traded. In contrast, temperature has a smaller effect, and it appears that year-on-year positive increases in the running average deviation of regional temperature from its time series mean are associated with less trading. However, two facts are worth noting in interpreting this result. First, water rights in the Chilean system are defined in terms of diversion and not consumptive use; if high temperatures increase crop evapotranspiration, return flows from irrigated fields may decline with no associated real-time increase in perceived scarcity for many or most diverting parties. In other words, the institutions governing the water management system may not accurately convey this increased scarcity to users. Second, it may not be the case that warm years are associated with increased scarcity: El Niño events in Chile are associated with both increased annual temperature and precipitation. As a result, warm years are also associated with more rainfall, which is likely the dominant driver of water scarcity and ultimately market outcomes. Coefficient estimates on the interaction terms in column

(8) suggest that the marginal effect of medium-term climate anomalies varies with lagged subsidies. When computing average marginal effects, we find that precipitation continues to have a statistically significant impact, while temperature does not. In particular, a one-unit increase in precipitation anomaly decreases market sales by approximately 3.6% (significant at the 1% level). Using these aggregated market measures, it appears that market trading responds to precipitation trends, but evidence suggests warm years play a much smaller role.

We now explore whether these responses vary depending on the source of water. These results are presented in Table 2 and reveal important differences within the sample. First, subsidies seem to have a statistically significant association only with surface water transfers. The estimate is robust to inclusion of climate variables and indicates that a 10% increase in subsidies is associated with an increase of about 0.6-0.7% in transfers for surface water rights, similar to the findings from Table 1. Groundwater rights, in contrast, do not change hands in response to lagged subsidy disbursements. This difference can be explained, in part, by the crucial role that conveyance structure plays in reducing transaction costs; the subsidy program targets such infrastructure, which, as noted by **?**, remains scarce in many regions of the country. Groundwater could be less susceptible to these constraints as intra-basin trading does not necessarily require the transportation of water, but rather the spatial shift in pumping effort. Furthermore, where the subsidy program targets on-farm irrigation infrastructure to improve efficiency, pressurization of existing distribution systems to replace flood irrigation is likely a priority. This will tend not to free up water on groundwater-irrigated farms, as groundwater systems are already pressurized.

Table 1 suggests dry years lead to more transactions in the water market. The estimates from Table 2 are consistent: for both types, coefficient estimates for precipitation anomalies are negative and significant at the 1% percent level; furthermore, the marginal effects implied by column (3) for surface water (-0.31) is larger than that from and (6) for groundwater (-0.19). Surface water access relies heavily on snowpack, which is much more likely to be directly affected by year-to-year variation in precipitation. Due to the high fixed costs of drilling a well, surface diverters may be inclined to make up shortfalls in times of scarcity on the surface water market before turning to groundwater. Due to the storage capacity of aquifers, groundwater users will be buffered against scarcity in the short term. Although recharge declines during drought and water tables may sink (which affects the net returns to pumping), these impacts are likely to be lesser than those felt by surface water users. Overall, relatively dry years appear to lead to an increase in the volume of transaction after adjusting for time and geographical factors as well as water source type.

With regard to temperature, Table 1 revealed only a weak association. Table 2 documents an asymmetric effect by source type: High temperatures are associated with a decrease in

Table 2: Panel Estimation Results by Source

	Surface			Groundwater		
	(1)	(2)	(3)	(4)	(5)	(6)
log[Subs]	0.07***	0.07***	0.06***	0.01	-0.00	-0.01
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Precip (5y)	-0.74***		-0.82***	-0.85***		-0.65***
	(0.16)		(0.16)	(0.15)		(0.15)
log[Subs] x 5y rain dev.	0.07***		0.08***	0.07***		0.07***
	(0.02)		(0.02)	(0.02)		(0.02)
Temp (5y)		-0.35**	-0.43***		0.01	-0.04
		(0.12)	(0.12)		(0.08)	(0.08)
log[Subs] x 5y temp dev.		0.04*	0.03		0.09***	0.09***
		(0.02)	(0.02)		(0.01)	(0.01)
Region FE	X	X	X	X	X	X
Yearly FE	X	X	X	X	X	X
Observations	540	540	540	540	540	540

Robust standard errors in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

surface water transactions (average marginal effect of -0.21), while groundwater trading reacts positively (average marginal effect of 0.52).

Finally, we also examine how firm characteristics of subsidy recipients may relate to the impact of subsidies on trading. The irrigation subsidy program encourages investment to increase the efficiency of water resource use in agricultural production in several ways. This includes cost-share payments for projects aimed at developing conveyance infrastructure as well as improving irrigation technology. These are available to firms of all sizes. We classified recipients into three categories: Large, medium, and small scale. These categories are officially determined as a function of the yearly tax revenue of a beneficiary, and it usually plays a part in the feasibility evaluation carried out by the authorities before approving subsidy disbursement. The small scale category includes small established firms, organizations of individuals, and individual users. It is important to recall that all beneficiaries of the program must hold water rights. For this estimation, we amend Equation 11 to include the share of subsidy value disbursed to a given firm size category in place of overall subsidy value. Dependent variable is still the logarithm of sales. The results of this analysis are presented in Table 3.

Table 3: Panel Estimation Results for Subsidy Recipients

	Surface				Groundwater			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Log[Sub %] (Large)	-0.67*			-0.52	-0.19			-0.23
	(0.30)			(0.30)	(0.29)			(0.29)
Log[Sub %] (Medium)		-0.32		0.20		0.18		0.05
		(0.27)		(0.29)		(0.28)		(0.31)
Log[Sub %] (Small)			0.81***	0.85***			-0.23	-0.23
			(0.22)	(0.23)			(0.21)	(0.24)
Precip (5y)	-0.41***	-0.39***	-0.34***	-0.35***	-0.27**	-0.26**	-0.28**	-0.28**
	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)
Temp (5y)	-0.30*	-0.30*	-0.29*	-0.29*	0.43***	0.45***	0.44***	0.44***
	(0.12)	(0.12)	(0.11)	(0.12)	(0.09)	(0.09)	(0.09)	(0.09)
Region FE	X	X	X	X	X	X	X	X
Yearly FE	X	X	X	X	X	X	X	X
Observations	540	540	540	540	540	540	540	540

Robust standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Higher volumes of subsidies for small-scale resource users in a given region-year are associated with more transfers, but only in the market for surface water rights. These estimates are robust to the inclusion of other subsidies, significant at the 0.1% level, and relatively large. In particular, a 10% increase in subsidies in the small scale sector is associated with about 8.5% increase in the volume of transaction in the market for surface water. The magnitude of the coefficient highlights that that the subsidy-trading associations apparent in Tables 1 and 2 are likely driven mostly by subsidies for these firms, which could have several explanations. Small-scale rights holders could face significant transaction costs due to individual constraints on access to credit to install on-farm infrastructure, less certainty in the legal standing of their rights, and/or a lack of relevant conveyance structures. That the relationship is detected only for surface water may suggest potential explanations: a) small-scale users may be less likely to be connected to conveyance infrastructure, and b) small-scale users may be more likely to rely on low-efficiency non-pressurized flood irrigation. Subsidies aimed at infrastructure and efficiency will target some of these issues and facilitate, at least in principle, transactions involving these parties.[4] These results encourage a deeper investi-

[4]Planned refinements to our subsidy dataset will allow for differentiation of subsidy payments for conveyance infrastructure vs. irrigation technology and wells.

gation of how subsidies interact with firm size, local and on-farm infrastructure, and other transaction costs that could be faced by firms of varying sizes.

In Appendix B.2 we explore the robustness of our results to 3- and 7-year running averages for our climatic variables. These do not appreciably alter the results. We also include an analysis of the wettest and driest regions in Chile at the individual (time series) level. This reveals substantial heterogeneity in the relationship between subsidy disbursements and trading, but because of the large spatial resolution of our cross-sectional units and inability to control for annual fixed effects, we view these estimates as less reliable and prefer to leave them to the appendix.

7 Discussion

The ability to routinely reallocate water across uses at low cost is one of the primary motivations for adopting a market-based approach to water management. However, empirical evidence of markets' effectiveness in this regard is limited. Previous work has identified gains from trade in several contexts, but typically in isolated cases (e.g., Grafton and Horne (2014) in the Murray-Darling and Ayres, Meng and Plantinga (2019) in California's Mojave Desert). Meanwhile, there is a broad awareness of high and sometimes prohibitive transaction costs in water markets (Loch, Wheeler and Settre, 2018; Leonard, Costello and Libecap, 2019). This paper is the first to use a rich nation-wide dataset to provide evidence about the extent to which market participants can successfully adapt to changing environmental conditions. Furthermore, we consider how a nationwide government irrigation subsidy program may affect market activity.

Fixed effects estimation reveals that persistent drought is associated with increased market transactions. This behavior arises both for surface water rights, which are constrained during drought due to reduced flows, and groundwater extraction rights. Despite the fact that groundwater remains physically accessible even in dry times, extraction can be restricted by the DGA during intense drought, leading to a demand for reallocation even within this market. While it is not possible specifically to characterize the motivations for these transactions, market reallocation to higher-valued uses as adaptation to shifting environmental conditions is likely. In addition, we find that subsidies for irrigation efficiency and infrastructure improvements are associated with increased trading, although this is manifested solely in the surface water market. Furthermore, any increased activity appears to be closely linked to firm size: only subsidies to small-scale agricultural producers are associated with increased trading. One interpretation of these results is that subsidy programs that target conveyance constraints and irrigation efficiency improvements hold promise for unlocking water transfers involving otherwise constrained, small-scale users.

Future work will consider how different uses of subsidy funds interact with firm size to relax constraints on trading. Exploring to what ends subsidy funds were ultimately put will reveal whether plausibly relaxing the constraints identified in this paper can indeed explain any associated increases in trading. Further work could also usefully investigate the "irrigation-efficiency paradox" in the Chilean case—i.e., to what extent subsidy disbursement encourages the sale of conserved water versus expansion of irrigated acreage via intensification (Grafton et al., 2018).

Communities across the globe are currently grappling with the question of which water management institutions will best suit their future needs in a changing climate. Water resources in arid areas often already suffer from mismanagement and misallocation (some remain in pure open access), and future increases in both scarcity and environmental variability will only increase the benefits of flexible institutions. As a result, there is a pressing need for a better understanding of whether and how a market approach can effectively produce accurate price signals and facilitate adaptation. This work suggests that markets can deliver, while also recognizing the role that government actions may play in reducing transaction costs.

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A Proof

A.1 Cap is known with certainty

Following the solution proposed by Pommeret and Schubert (2018), consider the case in which the cap in the second period is known with certainty. The Bellman equation for the firm's problem is given by:

$$\begin{aligned} V_{i1}(K_{i0}, W_{i1})) = \min_{Q_{i1}, I_{i1}} \Big\{ & C_i(Q_{i1}, K_{i0} + I_{i1}) + kI_{i1} - p_1 \left(W_{i1} - (\bar{U}_i - Q_{i1}) \right) \\ & + \delta V_{i2}(K_{i1}, W_{i2})) \Big\} \end{aligned} \tag{A.1}$$

The first order conditions in period 2 are thus given by:

$$\frac{\partial C_i(\bullet)}{\partial Q_{i2}} = p_2 \tag{A.2}$$

$$-\frac{\partial C_i(\bullet)}{\partial K_{i2}} = k \tag{A.3}$$

Going back in time, the first order conditions for period 1 are:

$$\frac{\partial C_i(\bullet)}{\partial Q_{i1}} = p_1 \tag{A.4}$$

$$-\frac{\partial C_i(\bullet)}{\partial K_{i1}} = k(1-\delta) \tag{A.5}$$

Because aggregate levels are the envelope of firm's individual levels, optimal behavior implies:

$$-\frac{\partial C(\bullet)}{\partial K_2} = k \tag{A.6}$$

$$-\frac{\partial C(\bullet)}{\partial K_1} = k(1-\delta) \tag{A.7}$$

which yields:

$$K_2^* = \left(\frac{\beta c}{k} Q_2^{*\alpha} \right)^{\frac{1}{1+\beta}} \tag{A.8}$$

$$K_1^* = \left(\frac{\beta c}{k(1-\delta)} Q_1^{*\alpha} \right)^{\frac{1}{1+\beta}} \tag{A.9}$$

and

$$\frac{\partial C(\bullet)}{\partial Q_2} = \alpha c \left(\frac{k}{\beta c}\right)^{\frac{\beta}{1+\beta}} {Q_2^*}^{\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.10}$$

$$\frac{\partial C(\bullet)}{\partial Q_1} = \alpha c \left(\frac{k(1-\delta)}{\beta c}\right)^{\frac{\beta}{1+\beta}} {Q_1^*}^{\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.11}$$

This relationship suggest that the inter-temporal relationship between prices is given by:

$$\frac{\partial C(\bullet)}{\partial Q_1} = \delta \frac{\partial C(\bullet)}{\partial Q_2} \tag{A.12}$$

which is equivalent to:

$$\left(\left(\frac{1-\delta}{\delta}\right)^{\beta} \frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}} Q_1^* = Q_2^* \tag{A.13}$$

Finally, the market clearing condition implies:

$$Q_1^* + Q_2^* = \eta(q) \tag{A.14}$$

which results in the optimal total water consumption reduction in period one:

$$Q_1^* = \frac{\eta(q)}{1 + \left(\left(\frac{1-\delta}{\delta}\right)^{\beta} \frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}}} \tag{A.15}$$

with $q = \{0, 1\}$.

Equation A.15 indicates that optimal water consumption reduction is a fixed fraction of the total mandated reduction. Trivially, it follows that Q_1^* is decreasing in q and $\bar{\Delta}$, and that K_1^* is decreasing in k.

A.2 Cap is uncertain

Consider the case in which the cap in extraction is uncertain. The firms' problem is now given by the following Bellman equation:

$$\begin{aligned} V_{i1}(K_{i0}, W_{i1})) = \min_{Q_{i1}, I_{i1}} \big\{ & C_i(Q_{i1}, K_{i0} + I_{i1}) + kI_{i1} - p_1 \left(W_{i1} - (\bar{U}_i - Q_{i1})\right) \\ & + \delta \mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2}))\right] \big\} \end{aligned} \tag{A.16}$$

with

$$\mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2})\right] = qV_{i2}(K_{i1}, W_{i1} + \bar{\Delta}_i)) + (1-q)V_{i2}(K_{i1}, W_{i1} - \underline{\Delta}_i)) \tag{A.17}$$

Similarly, this problem can be solved using backward induction. First, consider the case in which the cap is increased, $W_1 + \bar{\Delta} < \bar{U}$. The value function at period 2 is given by:

$$V_{i2}(K_{i1}, W_{i1} + \bar{\Delta}_i) = \min_{Q_{i2}, I_{i2}} \left\{ C_i(\bar{Q}_{i2}, \bar{K}_{i1} + \bar{I}_{i2}) + k\bar{I}_{i2} - \bar{p}_2 \left(W_{i1} + \bar{\Delta}_i - (\bar{U}_i - \bar{Q}_{i2}) \right) \right\} \tag{A.18}$$

with probability q. Second, consider the case in which the cap is decreased, $W_1 - \underline{\Delta} < \bar{U}$. The value function for this state of the world is given by:

$$V_{i2}(K_{i1}, W_{i1} - \underline{\Delta}_i) = \min_{Q_{i2}, I_{i2}} \left\{ C_i(\underline{Q}_{i2}, \underline{K}_{i1} + \underline{I}_{i2}) + k\underline{I}_{i2} - \underline{p}_2 \left(W_{i1} - \underline{\Delta}_i - (\bar{U}_i - \underline{Q}_{i2}) \right) \right\} \tag{A.19}$$

with probability $1 - q$.

To keep track of the relevant scenarios, variables in the case of an increase in the extraction cap are denoted with a bar, while those in the case of a decrease in the extraction cap are denoted with an underscore, respectively. The first order conditions in period 2 are then given by:

$$\frac{\partial C_i(\bullet)}{\partial \bar{Q}_{i2}} = \bar{p}_2 \tag{A.20}$$

$$-\frac{\partial C_i(\bullet)}{\partial \bar{K}_{i2}} = k \tag{A.21}$$

and

$$\frac{\partial C_i(\bullet)}{\partial \underline{Q}_{i2}} = \underline{p}_2 \tag{A.22}$$

$$-\frac{\partial C_i(\bullet)}{\partial \underline{K}_{i2}} = k \tag{A.23}$$

Similarly, first order conditions for period 1 are:

$$\frac{\partial C_i(\bullet)}{\partial Q_{i1}} = p_1 \tag{A.24}$$

$$-\frac{\partial C_i(\bullet)}{\partial K_{i1}} = k(1 - \delta) \tag{A.25}$$

In addition to the previous notation, let # denote the solution for the scenario when there is uncertainty over the extraction cap. It follows that aggregate optimal investment satisfies:

$$\bar{K}_2^{\#} = \left(\frac{\beta c}{k}\bar{Q}_2^{*\alpha}\right)^{\frac{1}{1+\beta}} \tag{A.26}$$

$$\underline{K}_2^{\#} = \left(\frac{\beta c}{k}\underline{Q}_2^{*\alpha}\right)^{\frac{1}{1+\beta}} \tag{A.27}$$

$$K_1^{\#} = \left(\frac{\beta c}{k(1-\delta)}Q_1^{*\alpha}\right)^{\frac{1}{1+\beta}} \tag{A.28}$$

and

$$\frac{\partial C(\bullet)}{\partial \bar{Q}_2} = \alpha c \left(\frac{k}{\beta c}\right)^{\frac{\beta}{1+\beta}} \bar{Q}_2^{*\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.29}$$

$$\frac{\partial C(\bullet)}{\partial \underline{Q}_2} = \alpha c \left(\frac{k}{\beta c}\right)^{\frac{\beta}{1+\beta}} \underline{Q}_2^{*\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.30}$$

$$\frac{\partial C(\bullet)}{\partial Q_1} = \alpha c \left(\frac{k(1-\delta)}{\beta c}\right)^{\frac{\beta}{1+\beta}} Q_1^{*\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.31}$$

Total inter-temporal reduction in extraction is then given by:

$$\frac{\partial C(\bullet)}{\partial Q_1} = \delta \left(q\frac{\partial C(\bullet)}{\partial \bar{Q}_2} + (1-q)\frac{\partial C(\bullet)}{\partial \underline{Q}_2}\right) \tag{A.32}$$

which is equivalent to:

$$\left(\left(\frac{1-\delta}{\delta}\right)^{\beta}\frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}} Q_1^{\#} = \left(q\bar{Q}_2^{\#\frac{\alpha-(1+\beta)}{1+\beta}} + (1-q)\underline{Q}_2^{\#\frac{\alpha-(1+\beta)}{1+\beta}}\right)^{\frac{1+\beta}{\alpha-(1+\beta)}} \tag{A.33}$$

Finally, market clearing conditions imply:

$$\bar{Q}_2^{\#} = \eta(q) - (1-q)(\bar{\Delta} + \underline{\Delta}) - Q_1^{\#} \tag{A.34}$$

$$\underline{Q}_2^{\#} = \eta(q) - q(\bar{\Delta} + \underline{\Delta}) - Q_1^{\#} \tag{A.35}$$

Market clearing conditions along with equation A.33 provide the implicit optimal level of water consumption reduction under uncertainty. Note that optimal allocation balances the potential effects of having both too much or too little water in the next period.

A.3 The effect of uncertainty in extraction

First order conditions and market clearing conditions for both scenarios imply;

$$\frac{\partial C(Q_1^*, K_1^*)}{\partial Q_1} = \delta\frac{\partial C(\eta(q) - Q_1^*, K_1^*)}{\partial Q_1} \tag{A.36}$$

and

$$\frac{\partial C(Q_1^{\#}, K_1^{\#})}{\partial Q_1} = \delta\left(q\frac{\partial C(\eta(q) - \bar{Q}_1^{\#}, \bar{K}_1^{\#})}{\partial Q_1} + (1-q)\frac{q\partial C(\eta(q) - \underline{Q}_1^{\#}, \underline{K}_1^{\#})}{\partial Q_1}\right) \tag{A.37}$$

$$= \delta\left(q\frac{\partial C(2(\bar{U} - W_1) - \bar{\Delta} - Q_1^{\#}, \bar{K}_1^{\#})}{\partial Q_1} + (1-q)\frac{q\partial C(2(\bar{U} - W_1) - \underline{\Delta} - Q_1^{\#}, \underline{K}_1^{\#})}{\partial Q_1}\right) \tag{A.38}$$

$$\tag{A.39}$$

which in turn implies:

$$\frac{\partial C(Q_1^{\#}, K_1^{\#})}{\partial Q_1} > \delta\frac{\partial C(\eta(q) - Q_1^{\#}, K_1^{\#})}{\partial Q_1} \tag{A.40}$$

Because $\partial C(\bullet)/\partial Q$ is proportional to $Q^{\frac{\alpha-(1+\beta)}{1+\beta}}$, $\partial C(\bullet)/\partial Q$ is convex in Q if $\alpha > 2(1+\beta)$ and concave otherwise. Evaluating this property in equations A.36 and A.40 implies that $Q_1^{\#} > Q_1^{*}$ when the marginal cost of reducing extraction is convex, while $Q_1^{\#} < Q_1^{*}$ when the marginal cost is concave.

B Supplementary Tables

B.1 Summary Statistics

Table B.1: Summary Statistics, by Region

	Mean Total Sales (#)	Mean Surface Sales (#)	Mean GW Sales (#)	Mean Annual Subsidy (Pesos)	Mean Annual Precip (mm/cm^2)	St. Dev. Annual Precip (mm/cm^2)	Mean Annual Temp (°C)	St. Dev. Annual Temp (°C)
De Antofagasta	14.39	11.81	2.17	3504.56	1.29	0.52	1.66	0.88
De Arica Y Parinacota	55.67	44.86	7.86	16421.52	7.41	2.60	12.30	0.77
De Atacama	52.86	42.53	8.97	29398.80	3.21	1.53	3.52	0.64
De Aysen	12.03	11.44	0.33	5034.75	49.12	9.39	3.83	1.05
De Coquimbo	366.47	288.22	26.69	106024.92	11.32	4.28	8.07	1.28
De La Araucania	104.00	91.39	3.03	38227.46	46.36	9.54	9.00	0.56
De Los Lagos	23.94	19.72	4.03	14895.26	59.06	10.80	8.75	0.57
De Los Rios	23.06	20.47	2.11	14034.05	56.56	10.90	9.36	0.57
De Magallanes	3.50	2.89	0.47	2456.61	48.58	9.80	5.00	0.57
De O'Higgins	452.28	377.69	23.42	74683.63	16.54	5.69	10.99	1.17
De Tarapaca	23.47	8.97	12.25	3292.81	3.28	1.40	13.09	1.12
De Valparaiso	376.06	239.67	94.97	63484.14	8.06	3.15	9.95	1.88
Del Bio Bio	231.11	195.47	8.42	74540.02	34.00	7.91	10.15	0.59
Del Maule	544.33	487.33	11.36	207580.24	23.64	6.99	10.99	0.69
Metropolitana	1454.28	1029.44	204.11	37926.54	11.55	4.15	8.79	1.69

B.2 Additional Tables

In addition to the analysis in the main body of the paper, this section compiles several additional analysis for different explanatory variables and subsamples.

Table B.2: Panel Estimation Results with 3 year running average

	log[Transfers]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log[Subs]	0.08***	0.09***	0.32***	0.08***	0.29***	0.08***	0.29***	0.07***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Precip (3y)	-0.24**		0.31	-0.71***			0.28	-0.71***
	(0.08)		(0.18)	(0.14)			(0.18)	(0.14)
Temp (3y)		-0.06			0.05	-0.19	0.05	-0.17
		(0.10)			(0.14)	(0.12)	(0.15)	(0.11)
log[Subs] x 3y rain dev.			-0.01	0.07***			0.01	0.07***
			(0.02)	(0.02)			(0.02)	(0.02)
log[Subs] x 3y temp dev.					0.07***	0.02	0.08***	0.01
					(0.02)	(0.02)	(0.02)	(0.02)
Region FE	X	X		X		X		X
Yearly FE	X	X	X	X	X	X	X	X
Observations	540	540	540	540	540	540	540	540

Robust standard errors in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

To explore how pre-existing climatic conditions affect these responses we split the sample and examine the transfers in the most arid regions of Chile. Namely, the regions of Antofagasta, Tarapaca, Atacama, and Arica.[5] We replicate the analysis for wet regions. Namely, the regions of Rios, Lagos, Magallanes, and Araucania.[6] There results are presented in Tables B.4 and B.5.

Subsidies show a statistically significant association in many of the driest regions. We must note, however, that given the sample size and the current resolution of the analysis (i.e., at the region level), these current results are merely illustrative.[7]

[5]These names are simplified for clarity. The proper names are "Región de Antofagasta," "Región de Tarapacá," "Región de Atacama," and "Región de Arica y Parinacota."

[6]These names are also simplified for clarity. The proper names are "Región de los Ríos," "Región de los Lagos," "Región de Magallanes y la Antártica Chilena", and "Región de la Araucanía."

[7]By undertaking the analysis at the regional level, we lose the ability to control for yearly-fixed effect, and thus much of time-specific variation is captured in the coefficients of interest, potentially biasing the estimates. We are currently working to increase the resolution to the basin level, which would allow us to undertake such regional analysis with a panel at finer scale.

Table B.3: Panel Estimation Results with 7 year running average

	log[Transfers]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log[Subs]	0.07***	0.09***	0.32***	0.08***	0.28***	0.07***	0.29***	0.05**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Precip (7y)	-0.42***		0.14	-0.96***			0.11	-1.14***
	(0.09)		(0.22)	(0.16)			(0.22)	(0.18)
Temp (7y)		-0.07			-0.08	-0.40**	-0.03	-0.62***
		(0.11)			(0.17)	(0.13)	(0.17)	(0.15)
log[Subs] x 7y rain dev.			0.02	0.08***			0.04	0.09***
			(0.03)	(0.02)			(0.03)	(0.02)
log[Subs] x 7y temp dev.					0.10***	0.06**	0.10***	0.06**
					(0.02)	(0.02)	(0.02)	(0.02)
Region FE	X	X		X		X		X
Yearly FE	X	X	X	X	X	X	X	X
Observations	540	540	540	540	540	540	540	540

Robust standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B.4: Panel Estimation Results for Dry Regions

	Surface				Groundwater			
	(Ant)	(Tar)	(Ata)	(Ari)	(Ant)	(Tar)	(Ata)	(Ari)
log[Subs]	-0.01	0.38***	0.26***	-0.20***	-0.06	0.20***	0.14***	-0.54*
	(0.08)	(0.05)	(0.05)	(0.06)	(0.05)	(0.03)	(0.03)	(0.21)
Precip (5y)	-1.03*	-1.03	0.01	0.99	0.24	-0.13	-0.24	-1.71
	(0.50)	(0.73)	(0.28)	(0.55)	(0.20)	(0.16)	(0.22)	(1.27)
Temp (5y)	0.83**	-0.07	0.01	1.02	0.01	0.01	-0.22	4.05*
	(0.30)	(0.18)	(0.28)	(0.70)	(0.09)	(0.10)	(0.19)	(1.88)
log[Subs] x 5y rain dev.	-0.05	-0.40**	0.16**	-0.12*	-0.22***	-0.30***	0.17***	0.12
	(0.06)	(0.13)	(0.05)	(0.06)	(0.03)	(0.06)	(0.03)	(0.14)
log[Subs] x 5y temp dev.	0.21	-0.36***	-0.12	0.29**	0.18**	-0.17**	-0.01	0.57*
	(0.12)	(0.07)	(0.08)	(0.09)	(0.06)	(0.06)	(0.05)	(0.25)
Region FE	X	X	X	X	X	X	X	X
Yearly FE								
Observations	36	36	36	36	36	36	36	36

Robust standard errors in parentheses. Ant: Antofagasta, Tar: Tarapaca, Ata: Atacama, Ari: Arica
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B.5: Panel Estimation Results for Wet Regions

	Surface				Grounwater			
	(Rio)	(Lag)	(Mag)	(Ara)	(Rio)	(Lag)	(Mag)	(Ara)
log[Subs]	0.20***	0.02	-0.97**	-0.09	0.02	-0.10	-0.80**	-0.04
	(0.05)	(0.14)	(0.27)	(0.04)	(0.03)	(0.15)	(0.27)	(0.03)
Precip (5y)	-1.98*	-2.17	-1.09	1.05***	-0.07	0.83	-1.07	0.25
	(0.87)	(1.88)	(0.85)	(0.28)	(0.36)	(0.92)	(0.89)	(0.13)
Temp (5y)	0.17	1.17	2.75	1.29*	0.39	-2.19	3.03	0.48
	(0.50)	(2.17)	(2.27)	(0.58)	(0.27)	(1.22)	(2.48)	(0.32)
log[Subs] x 5y rain dev.	0.17	0.27	0.15	0.01	0.09	0.03	0.04	0.00
	(0.08)	(0.17)	(0.11)	(0.06)	(0.07)	(0.11)	(0.13)	(0.04)
log[Subs] x 5y temp dev.	-0.47***	0.19	1.09**	0.08	-0.39***	0.65***	0.78*	0.11
	(0.07)	(0.19)	(0.35)	(0.12)	(0.06)	(0.14)	(0.37)	(0.10)
Region FE	X	X	X	X	X	X	X	X
Yearly FE								
Observations	36	36	36	36	36	36	36	36

Robust standard errors in parentheses. Rio: Rios, Lag: Lagos, Mag: Magallanes, Ara: Araucania.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$