An agro-economic approach to framing perennial farm-scale water resources demand management for water rights markets

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Abstract

Water rights and corresponding markets work to address water scarcity by establishing tradable, limited-access permits to water resources. Under certain water rights law, rights holders face uncertainty in terms of right allocation value, which is set annually based on reservoir storage, expected inflow, and expected future conditions. Such is the case in the Elqui Valley, Chile, where the economy is driven by agriculture, which requires water rights to ensure profitable yields due to a mismatch between the season of precipitation (May-August) and growing season (September-April). Perennial crop farmers address allocation uncertainty by securing additional water. A farm-scale agro-economic demand modelling framework is developed which utilizes the temporary transferability of rights to describe how grape famers may engage optimally in water markets to maximize annual profits (2000-2015), and produces an upper bound on grape farmer price negotiation space for desired allocation transactions. The results show grape farmers holding 1.0 and 2.25 water rights per-hectare could increase expected profits by 98% and 27%, respectively by engaging optimally in the temporary water market. Over the period evaluated, a grape farmer holding a single water right may expect to engage in market activity 80% of years; two rights require farmers to engage during 30% of years; with seven rights market engagement is avoided. The broader insights of the research suggest where rights holders accurately assess the value of water, optimal engagement strategies can be developed that add to farm-scale profitability, and act as an assessment of whether existing rights ownership matches risk tolerance.

Keywords: tradable; allocation; optimal; surplus

1 Introduction

Adaptive water resources and agricultural management strategies must be developed collaboratively to address increasing hydrologic uncertainty. While much research has been dedicated to top-down water resources management decision making, Integrated Water Resources Management (IWRM), Strategic Vision Planning (SVP), and other structured water resources planning guidance suggest an equal, bottom-up effort is warranted to inform agricultural decision making processes at the farm scale (Röckstrom 2000; Dungumaro and Madulu 2003; Loucks et al. 2005; Palmer et al. 2013; Watson 2014). In regions with temporal mismatches between growing and wet season, which may render rain fed cropping unfeasible, farmers must act to secure adequate supplies of water to maximize crop production. Where surface water resources can be relied upon to provide for irrigated agriculture, water rights, as a means of efficient centralized allocation decision making, have emerged. Laws governing the distribution, ability to buy and sell, and whether the allocation value of a right is fixed or uncertain and determined by water availability, play a central role in rights holder decision making.

For some regions already managed through water rights, entitlements or allocations (e.g. Australia, Chile, and Mexico), and those with emergent water law and markets (Roson 2017), uncertainty in allocation value is a function of natural climate variability, and may increase with longer lead time (from the allocation issuance date) (Rosegrant and Gazmuri S. 1995; Freebairn and Quiggin 2006; Grantham and Viers 2014; Syme 2014; Delorit, Gonzalez Ortuya, and Block 2017b). In these regions, water allocations are determined using a combination of reservoir storage, expected inflow, and expected future conditions. Decisions are made by the reservoir manager, but the uncertainty is predominantly held by the water right holder, and usually in the form of reduced allocations (Delorit, Gonzalez Ortuya, and Block 2017a). Allocation decisions may not be truly reflective of the reservoir's ability to supply. Rights holders engaged in the production of goods which require water as an input, specifically farmers, face additional exogenous uncertainty which may alleviate or compound allocation uncertainty. Major production input parameters, or those which dominate production costs, such as fertilizer and labor, as well as expected crop market prices at harvest time may alter farmer decision making. Perennial crop farmers face additional risk in terms of long-term impacts of underwatering wood or vine plantings. Severely reduced allocations may damage or kill perennial crops, impacting not only current year, but subsequent year harvests. Instances of plant kill may require costly replanting if root-preserving allocations cannot be secured.

For legal structures where the annual per right allocation value is uncertain and subject to available supply, and transaction of rights (permanent and/or temporary) is permissible, rights holders may choose to engage in water rights market to secure additional or sell surplus water. When in need of additional supply, the core of the farmer's decision is choosing to engage in the water rights market only when water may be obtained at a cost which is less than the expected profit. Simply, the marginal benefits of participating in the market must be greater than the marginal costs or expected losses if plant kill is expected. To optimize market engagement, water right holding farmers must understand the complex interactions of water allocations, crop phenology, and markets for inputs (water, fertilizer, labor) and outputs. Amalgamating these complex interactions to evaluate farm-scale water resource decision making, as a means of satisfying demand for bottom-up water resources management planning, warrants further study.

1.1 Chilean Water Markets

Chile's 1981 Water Code (WC) applies free-market economic principles to surface water resources management, and establishes the framework by which water rights are governed. The WC was initially viewed somewhat positively, and celebrated by *some* as a successful application of Coasean Economics (Rosegrant and Binswanger 1994; Holden and Thobani 1996; Briscoe, Anguita, and Pena 1998; Hearne and Donoso 2014; Molinos-Senante, Donoso, and Sala-Garrido 2016; Chikozho and Kujinga 2017). Most notably The World Bank and International Food Policy and Research Institute (IFPRI), have recommended the WC as a model for international water resources management reform, particularly for developing countries.

The Coase Theorem, in terms of water markets, postulates that regardless of the initial allocation of water rights among profit maximizing agents, trading of rights will result in Pareto efficiency, provided transaction costs are "low", preferably non-existent. That is, parties will naturally bargain the most mutually beneficial outcome, provided rights ownership is secure and transactions are allowed by law. The pillars of the Coase Theorem are written into the WC and stipulate that the distribution of rights from the Chilean federal government to perspective rights holders be costless. Each right, initially endowed free of cost to prospective water rights holders, is equally valued in terms of its written, mean annual maximum flow; there is no hierarchy of ownership. The annual allocation value can vary, unlike other markets in which it is fixed, and is set using a combination of reservoir storage, expected inflow, and expected future conditions. Simply, each water right carries with it a written value, equal to all water rights within a given basin. The annual allocation value delivered may not exceed the written value, but may be less, dependent upon storage and expectations of future conditions**.** Aside from nominal fees paid to maintain canals, the allocation is provided without cost. Water rights can be sold permanently or leased temporarily by their owner, ideally in exchange for compensation.

The WC is crafted to limit institutional barriers to transactions to provide for a rapid reallocation of rights to the most economically efficient use. Permanent transactions occur over longer periods of time and may describe macro-scale market trends (e.g. transfers of rights over years, from agriculture to mining as it becomes more profitable than agriculture). Opposingly, temporary transactions account for finer, seasonal, scale efficiencies (e.g. a market price differential increase generates transfers from one crop-type farmer to another) and may generally be preferred because of the annual uncertainty of the value assigned to water rights.

While celebrated by some, since its implementation, the WC has been the subject of some social and environmental, and many economic criticisms, which are repeated throughout literature (Bauer 1998; Bauer 2004; Borgias and Bauer 2017; Brehm and Quiroz 1995; Donoso 2006; Hearne and Easter 1995; Ríos and Quiroz 1995; Burgos 2017):

1. Ownership uncertainty:
    a. Rights holder registries are either incomplete or inconsistent, and many rights and transfers are not recorded. This makes permanent and/or temporary transfers between buyer and seller difficult, if not impossible.
        i. This implies property rights, while perhaps initially (1981) well defined, are no longer certain.
    b. Therefore, rights holder decision making is hampered because they cannot accurately assess social benefits and economic efficiency of rights use due to a lack of accurate information in the water rights holder registry. The holder is thus unable to determine a fair market value of their right.
        i. Economic equilibrium cannot be achieved where the value of the resource is disputed. Rights holders may choose to retain their right while a more economically efficient use may exist. This is partially because water is not priced in Chile; there is no benchmark to which permanent and temporary water right sale prices may be calibrated.
    c. Although permanent transactions are uncommon, due to the uncertainty of the registry, rights holders seek to sell more water than they are entitled to. All permanent transactions require a legal rights study, and discrepancies in ownership may increase the length of time and the cost required to complete a transaction.

   d. Spillover volumes are claimed by others. This has created a classic freerider issue, and has led to conflict between right holders, particularly when rights are sold or leased temporarily. This issue may be present, but is possible only when the point of extraction changes.
   e. The Chilean Ministry of Public Works – Dirrecion de Aguas (DGA), the federal agency mandated by the WC to oversee management of surface waters, has limited ability to mediate. More often, administrative courts, generally unfamiliar with the WC, decide ownership disputes.
   f. Investment in conveyance infrastructure has been deferred. System losses are estimated between 20-40%.
2. Transaction and water right purchase costs:
   a. There are transaction costs, beyond agreed upon sale price. Common costs include permitting, right registration, and water inspection by DGA. Rights holders, in many cases, must hire legal counsel to assist with these matters at additional cost. There is no consensus over the magnitude of these costs. Furthermore, the market price of permanent water rights, dependent upon the basin, have risen between 40% and 240% (1986-2000), which has led to increased temporary leasing of water rights (de la Luz Domper 2009).

These findings suggest that since the time the WC was initially enacted, the mechanisms required for the free-market equilibrium to be achieved and maintained have eroded, not developed organically (“The Invisible Hand”) as intended, or have been overcome by external, unforeseen factors.

The contrasting evaluations of WC performance, and the fact that it is relatively unchanged in nearly 40 years, at least in terms of water markets, suggests that sweeping, institutional-level policy changes that would address the inefficiencies discussed here are unlikely to be considered. Thus, an alternative approach to water market performance improvement, that functions within the constraints of existing water law, and targets water right holder interactions may be necessary. While a variety of intervention techniques have been suggested, most research calls for a mixed quantitative and qualitative, multidisciplinary approach to addressing the economic inefficiencies of Chilean water markets. Active informal or temporary trading markets have emerged that alleviate transaction costs (Hearne and Easter 1995; Hearne and Easter 1997; Bauer 2010). These transactions are legal but unrecorded, and the intensity of market activity is related to water scarcity.

1.2 Study Area and Agricultural Economy: Elqui River Valley

The semi-arid Elqui River Valley of north-central Chile (Fig. 1) experiences many of the economic inefficiencies discussed above (Hearne and Easter 1995; Young et al. 2009). It rises 5,000 meters from sea level in the span of 150 kilometers east to the Andes and the boarder with Argentina, is just south of the Atacama Desert, and 500 kilometers due north of Santiago. The Valley area (<10,000 square kilometers) is relatively small, with 600,000 inhabitants drawing water resource needs almost entirely from the river, which is fed predominantly by summer (October – January) runoff from the El Tapado glacier and snow melt from the previous winter (May – August). Precipitation in the valley exhibits large interannual variability, with most of the 90-millimeter average annual total falling between May and August. Years of above and below normal precipitation are generally associated with the El Niño and La Niña phases of El Niño Southern Oscillation, respectively, and both correlate highly with Summer growing season streamflow (Verbist et al. 2010).

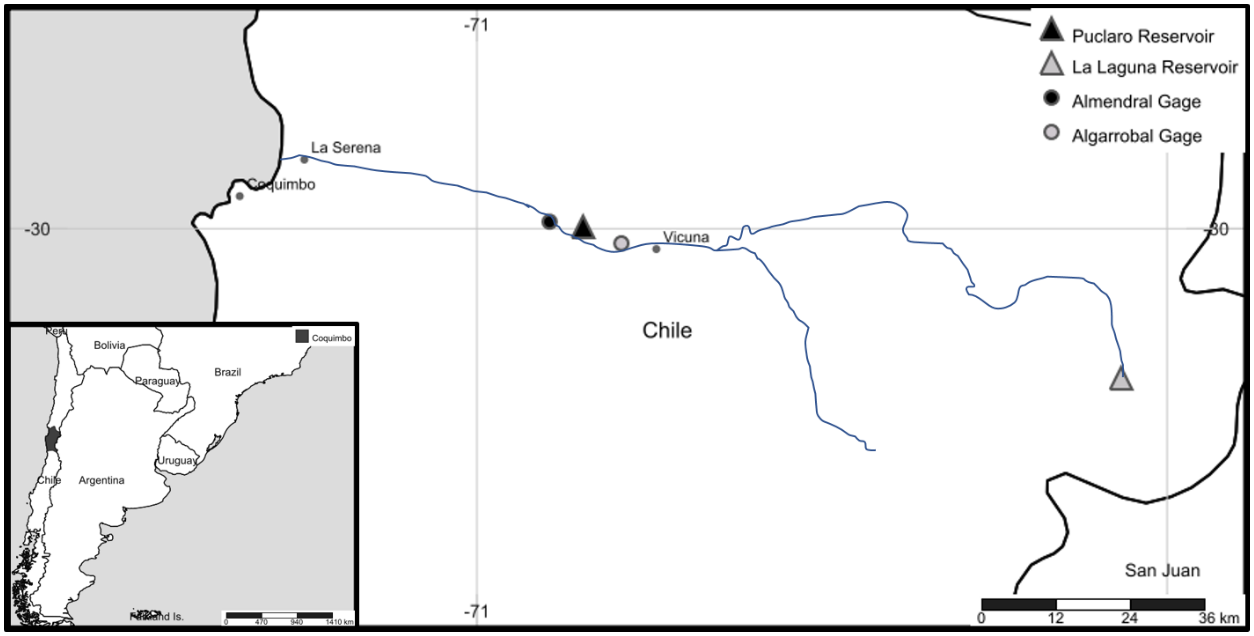


Figure 1. Location of Elqui Valley, Coquimbo Region, Chile

To manage the interannual variability in streamflow for agricultural production, the Chilean Ministry of Public Works built the Puclaro Reservoir in 1997, with a storage capacity of 200 million cubic meters. Since completion, Puclaro has been managed by a single, privately held water user association (WUA) (Junta de Vigilancia del Rio Elqui y sus Afluentes, JVRE). The JVRE is responsible for ensuring delivery of water to the mouths of nearly 120 water channel association and water community owned and maintained canals, which are comprised of water rights holding individuals and firms who share a common irrigation canal, from which individual allocations are drawn and used. These associations and communities, along with JVRE, are WUAs. The Elqui River Valley has approximately 25,000 fully allocated “acciones”, each not to exceed 1 liter per second average, annually. The JVRE is responsible for setting the per-accion annual allocation value on September 1st and uses Puclaro’s existing storage and estimates of expected inflow. Acciones are not the same as water rights, although each is a function of the other. In Chile, water rights can exceed 1 liter per second, but when summed across the Elqui Valley, can be expressed in accione equivalent units. Because acciones and water rights are translatable, acciones are the basis for the expression of the annual allocation value assigned by JVRE, and acciones is not a universal term, we proceed using water rights as a surrogate for acciones. During the most recent drought (2012-2015), allocation values fell below 0.20 liters per second according to JVRE, well below the 0.50 liters per second long-term average (Donoso 2006).

Most WUAs consist of farmers using surface, sprinkler, and drip irrigation systems. As such, agricultural exports lead the Valley’s economy, with grapes and other perennial fruit and vegetable crops holding the highest value, yet accounting for only 21% of the total irrigated area (Zunino et al. 2009). Grapes (12% of Elqui Valley irrigated area) are of notable value to the Elqui Valley, producing 14.35 metric tons and $9 million Chilean Pesos (CLP) on a per-hectare basis in 2015, according to Chile’s Office of Agricultural Policies and Studies (ODEPA). Aside from grapes, approximately 30 crop types are cultivated regularly in the Elqui Valley. Of the nearly 30,000 hectares reported as planted and irrigated, the mean distribution of each crop is 4% of the total irrigated area. Grapes (12%) and potatoes (24%) are planted most widely, while the next most prevalent crop, green beans, represent only 7% of the total area planted. Crops planted on an annual basis are predominantly planted downstream of Puclaro (91% of all annual crops), while grapes are planted mostly upstream of Puclaro (85% of all grapes) and account for 59% of all hectares planted upstream. While grapes are a potentially lucrative crop for Elqui Valley farmers, the perennial vines are at risk to failure in years where allocation values are low.

Unlike annual crop farmers, who may choose whether and what to plant, grape and other perennial crop farmers are tied to their cropping decisions for up to 50 years and face a 3-year yield latency if drought vine kill forces replanting (Verdegaal, Sumner, and Murdock 2016). In addition, the mean price of Elqui Valley grapes in Chilean markets have been variable (coefficient of variation = 0.47) between 2000 and 2015. Due to the volatile nature of the grape market, the distinct risks faced by grape producers in years of drought, and the uncertainty of annual water allocation values (a key input to grape production), farmers can take advantage of transfers to secure additional water to protect their vineyards and maximize profits (Nagues, Wheeler, and Zuo 2016).

Water market engagement, through permanent or temporary transactions, is the mechanism by which water is secured. Permanent transactions are those in which a water right is sold in perpetuity. In addition to the agreed upon sale price of the right, administrative costs (detailed above) are incurred. The record of transactions in the Elqui Valley is incomplete, however surveys of rights holders conclude permanent rights transactions are less common than temporary transactions, and occur mostly for small quantities of water, and between similar use types (e.g. farmer to farmer) (Hearne and Easter 1995; Maestu 2012; Bauer 2015; Chikozho and Kujinga 2017). Temporary transactions are more informal, as they do not require legal documentation, and coordination occurs only between the buyer, seller, and JVRE to reallocate Transaction price, length and/or volume are negotiated, provided right ownership is not disputed (Donoso 2006; Hearne and Donoso 2014; Molinos-Senante, Donoso, and Sala-Garrido 2016). JVRE tracks only the water transfer and does not maintain records of temporary transaction price. The market for temporary transactions is active (*personal communications*, JVRE), and has not been investigated in terms of farm-scale economic impact and is the central focus of this work.

Evidence suggests that temporary transactions occur with regularity both on an intra-canal and inter-canal basis in terms of both flow and volume, although data to support this claim is limited. To maximize profits, farmers must decide when the prospective benefit of procuring water outweighs the cost. Molinos-Senante, et al*.,* 2016 use a water use efficiency metric and find that farmers who trade in water markets in the Limari Valley, immediately south of the Elqui Valley, are more efficient in their water use than their counterparts who do not trade. They conclude that agricultural water productivity rises when farmers interact in water market, using non-radial data envelopment. Other recent analyses, applied to regions beyond, but with water law similar to Chile, have investigated both how water rights holders might adapt to increasing drought frequency by developing trading strategies based on categorical supply likelihoods (Adamson, Loch, and Schwabe 2017), and how forward contracts might improve water allocation efficiency where spot market mispricing and inequality in basin wealth challenge market efficiency (Bayer and Loch 2017).

Underlying each of these analyses are economic models which intend to evaluate how water ought to be distributed, given an uncertain future, and likely increased scarcity. Here we abstract from a market-scale analysis and focus primarily on developing an underlying water demand derivation framework using a coupled agro-econ model to assess when, and how aggressively, grape farmers in the Elqui Valley should engage in temporary market activity to maximize profit regardless of initial rights ownership. The demand framework proposed here may hold the potential for application to market-scale analyses and be coupled with models like those presented above which address both supply and demand interactions.

Temporary market transactions are the focus of this work because JVRE has stated the market for temporary transactions is active, although market informality prevents the development of a price revealing mechanism. Additionally, temporary transactions may be preferred by water rights holders due to the fact the uncertain nature of the annual, per-water right allocation means optimization may require annual market engagement, depending on initial rights ownership. As such, the remainder of this paper addresses the following question:

1) Given that temporary water markets lack a price revealing mechanism, can a comprehensive framework be developed such that a farmer may assess
    a. the value of their initial allocation, and
    b. determine the amount of water they need to produce maximum economic yield and its fair-market-value in the temporary water market?

2 Modeling Framework and Simulation

To approach modeling a farmer's optimal decision path to maximizing expected profit utilizing temporary transactions, it is prudent to begin by framing the problem in economic terms. This work treats grape farmers as agents seeking to make efficient decisions which maximize their expected profits, considering the levels and costs of inputs which are expected during the cropping season. To optimize, farmers must understand how the cumulative water allocation they will receive (per-right allocation times the number of rights currently owned) is likely to be converted to grape yield. Based upon an estimate of potential grape yield and expected market price, gross expected profit can be calculated, from which fixed and variable expected costs of operation must be subtracted to obtain net expected profit. By calculating net expected profit at a range of possible per-right allocation values, an optimal frontier of net expected profits can be presented as a farmer's decision space. Calculating the marginal benefits associated with yield increase from additional water, a farmer's total willingness to pay (TWTP) for water can be determined. The TWTP can be used as a decision rule by which farmers engage in the water market. This methodology is achieved by coupling a crop-water model with an economic model.

2.1 Crop-water model

Describing the dynamic and non-linear biologic relationship between water and grape yield is a critical step in constructing a model linking agricultural production to farm-level profit, and ultimately to optimal water market engagement by a farmer. Crop water modeling is used to calculate unconstrained grape yield and the corresponding sufficient water allocation (equivalent to the crop water requirement, CWR), as well as to simulate yields for observed per-water right allocation values. With these parameters, regression techniques are used to derive a biologic relationship between water and yield response.

Several crop water productivity models (AquaCrop, CERES, CropSyst, CropWat, DSSAT, etc…) have been developed to simulate crop yield response in herbaceous plants (Hunink and Droogers 2010). The Land and Water Division of The Food and Agricultural Organization (FAO) of the United Nations' AquaCrop (Raes et al. 2009), is a crop water model known for linking crop, water, and climate interactions, and is built to achieve a reasonable balance of accuracy, simplicity, and robustness, per the FAO. Users create and populate four module components to simulate location specific climate, crop characteristics, management techniques, and soil parameters. Sub-modules for management techniques (irrigation and field management) and soil parameters (profile and groundwater) are also utilized.

Location specific climate requires daily data for rainfall, maximum and minimum temperature, and reference evapotranspiration (ETo). Elqui Valley-wide precipitation and temperature data (daily, 1950-present), are readily available through the Chilean DGA. Data from the Algarrobal streamflow gauge on the Elqui River serves as inflow for the Puclaro reservoir and is near much of the grape production. ETo is calculated using the Modified Hargreaves equation (Eq. 1):

$$ET_o = 0.0023 \cdot 0.408 \cdot RA \cdot \left(T_{avg} + 17.8\right) \cdot TD^{0.5} \tag{1}$$

where RA is the extraterrestrial radiation (MJ m^{-2} d^{-1}) obtained from tables (Hargreaves 1994; Droogers and Allen 2002) and is multiplied by the constant 0.408 to convert to millimeters, T_{avg} is average mean daily temperature in degrees Celsius, and TD is the daily temperature range. The remaining constants are calculated by (Hargreaves, Hargreaves, and Riley 1985).

The crop characteristics module requires use of a pre-built crop profile or user specified phenology. AquaCrop is built primarily for crop yield simulation of herbaceous crops, however, (Hunink and Droogers 2010) construct a grape crop profile for AquaCrop which skillfully reproduces expected grape yields. Using the same critical crop characteristics, an Elqui Valley grape crop profile is created. Major parameters are shown in Table 1, as adapted from (Hunink and Droogers 2010).

Table 1. Critical grape crop characteristics module parameters

Parameter	**Value**
Growing season	September 15th – March 15th (180 days)
Planting density	2.0 x 4.0 meters, 1,250 per-hectare
Initial canopy cover	10% planted area, 8,000 cm^2
Maximum canopy cover (CCx)	70% planted area
Reference Harvest Index (HIo)	20% for Chile
Canopy Growth Coefficient (CGC)	0.2 (increase fraction soil cover per day)
Canopy Decline Coefficient (CDC)	0.08 (decrease fraction soil cover per day)

The irrigation management sub-module allows for selection of irrigation technique and whether crop yield simulation will be based upon 1) the net irrigation requirement (analogous to CWR determination), 2) generation of an irrigation schedule (daily distribution of water which results in CWR), or 3) user specification of an irrigation schedule. Generation of an irrigation schedule is selected to determine the grape CWR and corresponding unconstrained yield, while user specification of the irrigation schedule is selected to simulate yields for annual per-water right allocation values. When the irrigation schedule is specified by the user, the average annual per right allocation value is uniformly distributed to a daily scale per the historical monthly distribution of the right (72% of annual allocation value is typically distributed September - March (*personal communications,* JVRE). The per-right allocation value for the Elqui Valley is calculated using outflow from the Puclaro reservoir as measured at the Almendral streamflow gauge station (3 kilometers below Puclaro), less base flow. The irrigation method used by most grape farmers in the Elqui Valley is drip irrigation.

In the field management sub-module, no advanced techniques of in- and off-season soil preparation are assumed, which is consistent with practices in the Elqui Valley.

In the soil and groundwater profile sub-modules, two soil horizons are specified for the Elqui Valley which replicates in situ conditions at elevations where grapes are grown. Soils are a clay-sand and gravel mix, with the proportion of gravel increasing from 10% - 80% from the surface to 1.2 meters. Groundwater is set to an inaccessible depth (Melendez 1979).

After the modules are populated, simulations are conducted for 1999 - 2015 (Puclaro came online in 1999), with harvest set at March 15th. CWR and corresponding yield pairings are calculated along with annual yields corresponding to the per-right specified irrigation schedule. AquaCrop produces per-hectare pairings of water input and yield output. For the Elqui Valley this is described as the yield, in dry metric tons, corresponding to a case in which a farmer holds some number of water rights which provide an allocation equal to the annual irrigation value. Dry tons are converted to fresh yield by dividing by 0.20, which recognizes grapes as containing 20% dry and 80% wet matter (Hunink and Droogers 2010). Most grapes produced in the Elqui are brought to market before processing, and market prices are reported by ODEPA in fresh yields. It is widely accepted that grapevines are naturally long-lived (>100 years), and in terms of production for alcohol, “Old Vines” are often preferred for fruit quality (Lasko et al. 2003; Robinson, Harding, and Vouillamoz 2013) In addition, the high cost associated with vineyard replacement (planting and maintenance, trellis systems, foregone yield) drives farmers to avoid allocations which might result in vine kill.

2.2 Yield regression model

Crop yield response to water is a non-linear process, with yield dependent on both how much and when water is applied (Steduto et al. 2012). The yield and per-water right allocation paring outputs from AquaCrop exhibit this relationship. There are many approaches to yield calibration; the purpose of this research is to produce a coupled farm-scale agro-econ model, thus an approach approximating the continuous relationship between water and yield is viewed as sufficient for interpretability (Stone and Schlegel 2006; Hsiao et al. 2009). A simple regression of allocation value onto yield is selected. This relationship holds to the point where the CWR is achieved. Beyond the CWR, any additional application of water results in no increase in grape yield.

2.3 Agro-econ model

Coupled agricultural and economic models seek to optimize production of farmed goods. One such approach, Production Economics and Farm Management, describes diminishing returns from farm production with respect to changes in input costs and market prices received for goods produced (Chavas, Chambers, and Pope 2010). For the Elqui Valley, linking grape yield as a function of water to the costs of production and profits allows for estimation of the water's value to a farmer.

Input costs for grape production include fertilizer, labor, and administrative fees paid to JVRE and WUAs (Fig. 2). All costs are discounted to real November 2016 Chilean Pesos (CLP), using mean annual inflation rates reported by ODEPA. ODEPA provides fertilizer (CLP per kilogram bag) and farm labor prices (CLP per hour) monthly for 1999-2015, with the mean of the September - March price calculated as the seasonal prevailing agricultural wage rate. The JVRE and WUA administrative fees (CLP per year per water right) are obtained from the International Food and Policy Research Institute (McCarthy and Essam 2009). Benefits from farmer sale of grapes are assumed as the mean price of Elqui Valley produced grapes arriving at eight Chilean markets (month of harvest, 1995 - present) as available from ODEPA. While data provided by ODEPA generally extends from the mid-1990s to present, which limits the range of market and inputs price conditions available, seasonal allocation value have been calculated for the period (1950-2015) under the presumption Puclaro Reservoir existed prior to October 1999 (Delorit, Gonzalez Ortuya, and Block 2017a). That research produced similar descriptive statistics (max. = 1.4 L s^{-1}, min. = 0.13 L s^{-1}, μ = 0.44 L s^{-1}) versus (max. = 1.3 L s^{-1}, min. = 0.10 L s^{-1}, μ = 0.47 L s^{-1}) for the period considered here. In addition, the 2012-2015 hydrologic drought, the worst in modern times for the Elqui Valley, is captured in the period analyzed.

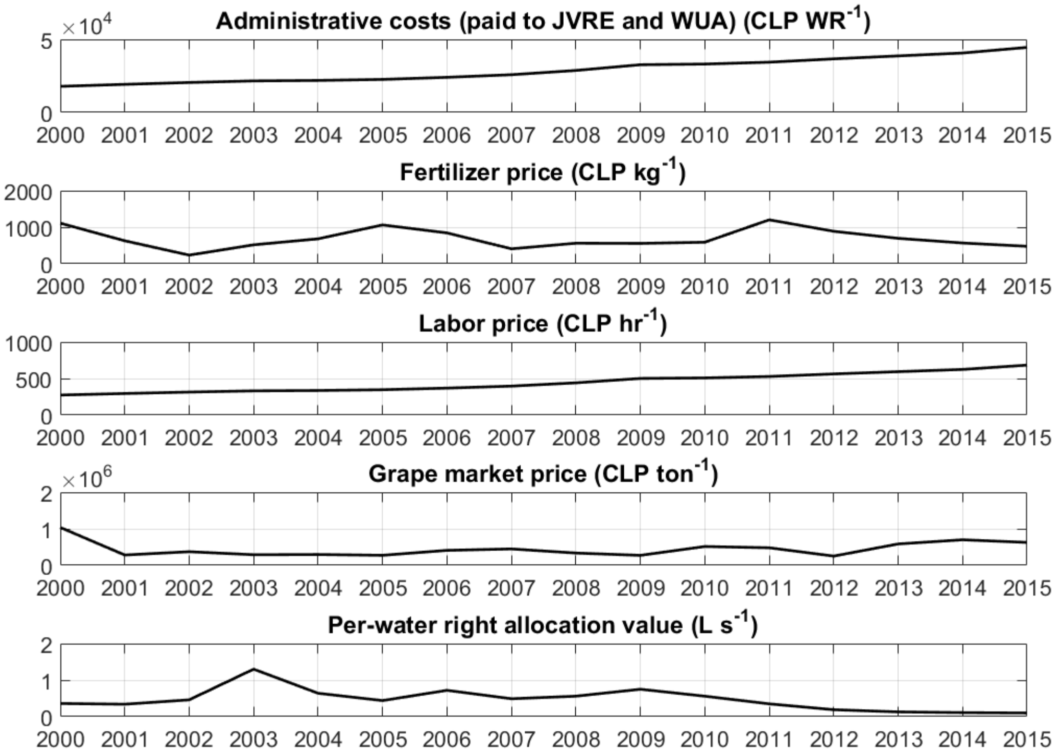


Figure 2. Agro-Econ model inputs (2000-2015)

There is a rich body of literature investigating farmer decision making, which predominantly points toward risk averse behavior under uncertainty (Gómez-Limón, Arriaza, and Riesgo 2003; Just 2003; Gardebroek, Chavez, and Lansink 2010; Nagues, Wheeler, and Zuo 2016). Some studies suggest farmers seek to maximize their von-Neumann-Morgenstern utility function holding farmers as both risk and downside averse, others suggest a spectrum of risk attitudes exists within farmer communities, especially where farmers are economically stratified (Ziervogel et al. 2005; Kosovac et al. 2017). However, to our knowledge there are no studies eliciting grape farmer risk attitudes in the Elqui Valley. In addition, an important component of this research aims to evaluate economically stratified grape farmer behavior, manifested here as differences in permanent water rights endowment.

Thus, rather than apply the von-Neumann-Morgenstern utility function, a more simplistic approach which treats farmers as risk neutral, maximizing expected profits for their water right endowment, is applied here. The model evaluates varied permanent water rights ownership strategies; a realistic response to allocation uncertainty by perennial crop-type farmers. Rather than specify a risk attitude, farmers are able to match their ownership to expected profit and market engagement outcomes, and decide whether their water rights ownership matches their risk attitude In water rights managed basins, perennial crop farmers lack crop-type decision flexibility their annual crop-type farmer counterparts possess (e.g. farmers making annual crop-type decisions can choose to plant drought tolerant crops in years of low allocation.) Thus, the primary mechanism available to grape and other perennial crop-type farmers to cope with allocation uncertainty is to secure additional water. The model is purposefully simplistic and is intended to balance complexity and interpretability of results, focused specifically on identifying both the frequency of expected temporary water market engagement and expected gains from trade across the endowment scenarios.

The basic model is constructed such that a set of expected annual optimal net profits are calculated for the range of feasible, per-right allocation values (0.05 – 1, varied by 0.05 liters per second), for which expected yields are achieved (Equation 2):

$$\boldsymbol{max}\, E[\pi_{t,w}] = E[P_t] \cdot E[Y_{t,w}] - [\textstyle\sum_{i=1}^{N}(E[C_{i_t}] \cdot E[Q_{i_{t,w}}] + E[Fees_t])], \quad t = 2000 - 2015 \qquad (2)$$

where $E[\pi_{t,w}]$ is expected net profit (CLP per-hectare) for each feasible water right allocation value w in year t,$E[\,P_t]$ is the March mean market price (CLP per metric ton) of grapes in year t, $E[Y_{t,w}]$ is the expected yield (metric tons per-hectare) of grapes produced for each feasible water right allocation value w in year t, $E[C_{i_t}]$ is the expected cost of input i in year t, $E[Q_{i_{t,w}}]$ is the quantity of input i for each feasible water right allocation value w in year t, and $E[Fees_t]$ is the expected per-right administrative fees paid to the JVRE and water community or canal association in year t. In simplified form, the objective function may be written as expected profit equal to expected benefits less the sum of actual costs. Where $\pi_{t,w}$ is maximized across feasible values of w for each year, the corresponding yield is referred to as the maximum economic yield (MEY), which is the yield level at which profits are maximized. Per-water right allocation values, w, are always subscripts. w is used to describe the range of feasible per-water right allocation values but can also take on specific values (e.g. water required to achieve a desired level of profit). As such, calculations of w can occur, as well as calculations of other variables, with specific values of w. Ultimately, w is a subscript, even though w may not appear as a subscript in the calculation. Expected profit is constrained by yield and variable input costs. Expected yield is a polynomial fit of yield and corresponding water right allocation value pairings to the CWR; above the CWR, yield is maximized.

Labor and fertilizer are modeled as a variable input costs. Expected cost per unit, C_{i_t}, is exogenously determined, however, the quantity of each input is modeled as a constant return to scale, which suggests an increasing level of input results in a proportional increase in output (Equations 3 & 4).

$$E[Q_{Labor_{t,w}}] = 6 \cdot Q_{L_{max}} \cdot \left(\frac{E[Y_{t,w}]}{E[Y_{max}]}\right) \tag{3}$$

$$E[Q_{Fert_{t,w}}] = Q_{F_{max}} \cdot \left(\frac{E[Y_{t,w}]}{E[Y_{max}]}\right) \tag{4}$$

where $E[Q_{Labor_{t,w}}]$ is the labor required (hours) to achieve the corresponding $E[Y_{t,w}]$, $6 \cdot Q_{L_{max}}$ is the seasonal labor requirement (hours) that achieves expected maximum yield ($E[Y_{max}]$), and the ratio of $E[Y_{t,w}]$ to $E[Y_{max}]$ forces the labor requirement to be proportional to the expected yield. $Q_{L_{max}}$ is set at 165 hours per month (Verdegaal, Sumner, and Murdock 2016). The fertilizer constraint, $E[Q_{Fert_{t,w}}]$ (kilograms per-hectare), follows a similar technique to achieve a corresponding $E[Y_{t,w}]$. $Q_{F_{max}}$ is the fertilizer application weight required to maximize yield and is set to 504 kilograms per-hectare (FAOSTAT 2015).

2.4 Farm-scale profit model

The agro-econ model produces annual optimal pairings of expected profit and water allocations on a per-hectare basis using a polynomial regression applied to each year, truncated to the CWR and corresponding profit. For each year simulated, the optimal expected profit corresponding to the per-right allocation value, calculated based upon streamflow at Almendral, is used to establish a "base case", where a farmer holds one water right for a single hectare. From the base case, alternative scenarios can be simulated in which farmers procure additional rights to achieve the CWR and maximize profit. Insight gained from these simulations include the minimum number of rights required to achieve MEY and farmer total willingness to pay (TWTP) for water deficit (Equation 5.)

$$TWTP_t = \pi_{\mathrm{MEY}_t} - \pi_{w_{t_{obs}}} \tag{5}$$

where π_{MEY_t} is calculated as the maximum expected profit achievable in year t, and$\pi_{w_{t_{obs}}}$is the optimal expected profit achieved by yield produced with the year t observed per-water right allocation $w_{t_{obs}}$. The TWTP represents the most a farmer should be willing to pay to secure water, fertilizer and labor required to achieve MEY, such that the cost of procuring the inputs is equal to the additional profit received.

The optimization is completed by forming a Lagrangian of the expected profit maximizing objective and the input cost constraints. The model calculates the marginal value λ_t (CLP per-hectare) of a one-ton yield increase for each year, for each constraint, including yield response to water. To determine the value of the water that corresponds to λ_t, the water required to produce the per-hectare yield corresponding to the annual water right allocation value and the allocation required to produce an additional ton of yield is calculated by solving Eq. 2 for subscript w. Taking their difference produces the marginal allocation requirement, $w_{t_{req}}$(Equation 6.)

$$w_{t_{req}} = w_{Y_t+1} - w_{Y_t} \tag{6}$$

The utility of water $U(w)$ (CLP) is calculated as the net benefit a grape farmer could achieve by utilizing a single right (Equation 7.)

$$U(w) = \left(\frac{\lambda_t}{w_{t_{req}}}\right) \cdot w_{t_{obs}} \tag{7}$$

$w_{t_{obs}}$ is the observed per-right allocation of water in year t. A positive relationship between utility and allocation value holds and is best fit by an exponential function (Griffin 2006). The second negative derivative of the utility function is synonymous with demand, $D(w)$ (Equation 8). In the case of water allocations, the area under the demand curve between two points (current allocation and desired allocation) is a farmer's total willingness to pay (TWTP) for the excess water required to maximize profit.

$$D(w) = -\frac{\partial^2 U}{\partial w^2} \tag{8}$$

In theory, a farmer should purchase water if market price of water desired is less than the TWTP, which signifies the benefit a farmer receives in terms of profit from increased yield exceeding the cost of the water. This relationship is evaluated on an annual basis to determine the frequency of expected market engagement and the excess benefits created by optimal participation (Equation 9.)

$$\pi_t^* = \pi_{MEY_t} - TWTP_t \tag{9}$$

where π_t^* is profit after market engagement and π_{MEY_t} is profit at MEY (market engagement not required to achieve MEY). This metric represents the profit a grape farmer could expect to make on a per-hectare basis if the TWTP is the market price of water.

3 Results

3.1 Crop-water and yield regression model

Grape CWR and corresponding yield are produced for 2000-2015. The CWR is calculated to be 0.70 liters per second with an unconstrained yield of 17.35 wet metric tons per-hectare. Unconstrained yield falls within the range of expected per-hectare maximums (FAOSTAT 2015) and are consistent with output as reported by ODEPA. The AquaCrop climate submodule includes atmospheric carbon dioxide concentrations as measured at Mauna Loa, which produce a slight positive linear trend in yield (Pearson's correlation coefficient = 0.99), at approximately 0.1 wet metric tons per-hectare. Thus, the mean of yield and CWR across 2000-2015 are appropriate and applied subsequently.

Annual simulations of water allocation value and yield pairings are regressed using a polynomial relationship (Fig. 3; Pearson's correlation coefficient = 0.96) and truncated where $Y_{t,w} = Y_{max}$, the maximized yield corresponding an allocation value equal to the CWR ($w \geq 0.70\ L\ s^{-1}$) (Equation 10); w is the range of allocation values (0.05 liters per second - 1.0 liters per second).

$$Y_{t,w} = \begin{cases} -78.6w^3 + 116.9w^2 - 20.1w \mid\ w \geq 0.05\ L\ s^{-1} \\ \qquad Y_{t,w} = Y_{max} = \ 17.4 \mid w \geq 0.70\ L\ s^{-1} \end{cases} \tag{10}$$

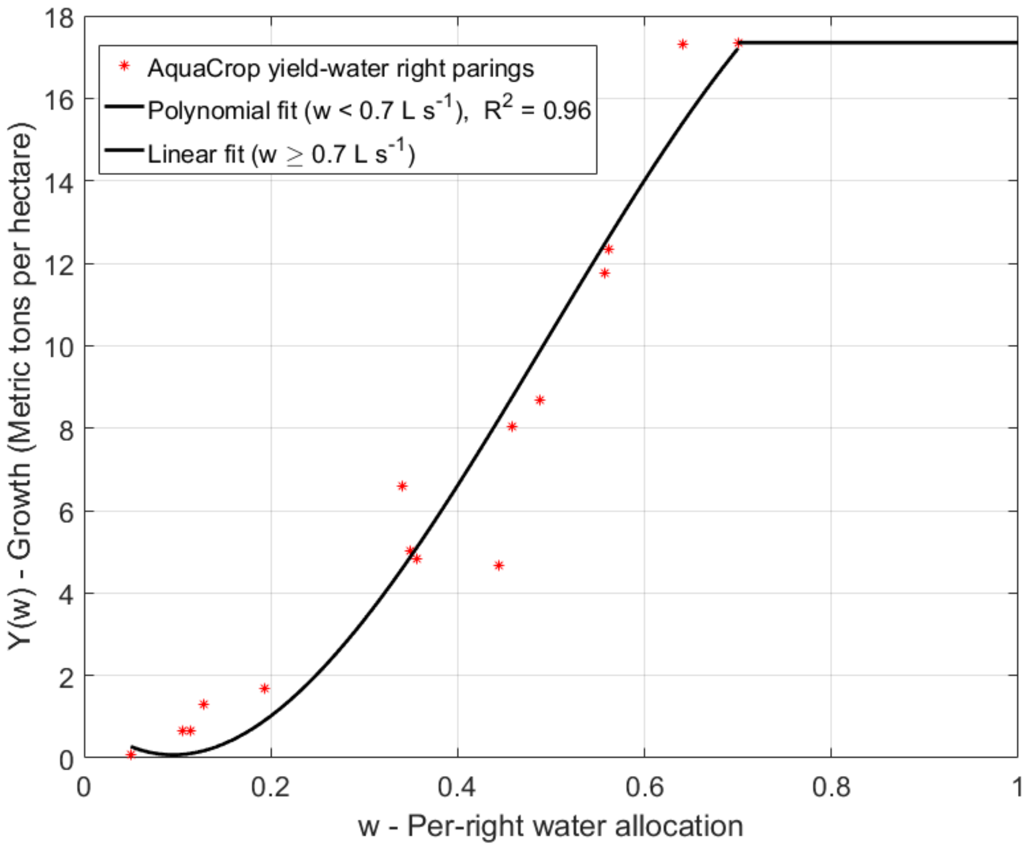


Figure 3. Grape yield response model

3.2 Farm-scale expected profit optimization, water rightsand demand for water

For each year (2000 - 2015), potential per-right water allocation value, and ensuing yield, the agro-econ model calculates the optimal level of the present value of gross profits, costs production, and optimal net present value of expected profit, hereafter referred to as optimal profit. Optimal expected profit is the largest profit a farmer could obtain at any per-water right allocation value. The set of annual optimal profit values forms an optimized frontier, from which a farmer can assess the level of optimal expected profit that can be achieved given a single water right, and subsequently contrast it with the expected annual MEY profit level (Fig. 4). The shape and vertical magnitude of the optimized frontier is annually variable, and dominated by the market price of grapes. The optimal expected profit at MEY is upper limit of the value of water as a function of grape yield. Unrealized expected profit resulting from holding a suboptimal number of water rights is calculated as vertical difference between the MEY expected profit and optimal expected profit for the actual per-right allocation for a given year.

Concurrently, the additional water required to achieve the MEY profit in any given year is the difference between 0.7 liters per second and the actual (observed) allocation value. This represents a farmer's tradeoffs between expected profit and water procurement. For example, in 2000, securing 0.34 liters per second (less than 1 additional water right) increases per-hectare expected profit by 10 million CLP. In contrast, for 2012, 0.51 liters per second (greater than 2.5 additional water rights) results in per-hectare expected profit increases of 3 million CLP. MEY expected profit variability for these years is explained by the fact that Elqui Valley produced grapes were nearly eight times more valuable in Chilean markets in 2000 than 2012.

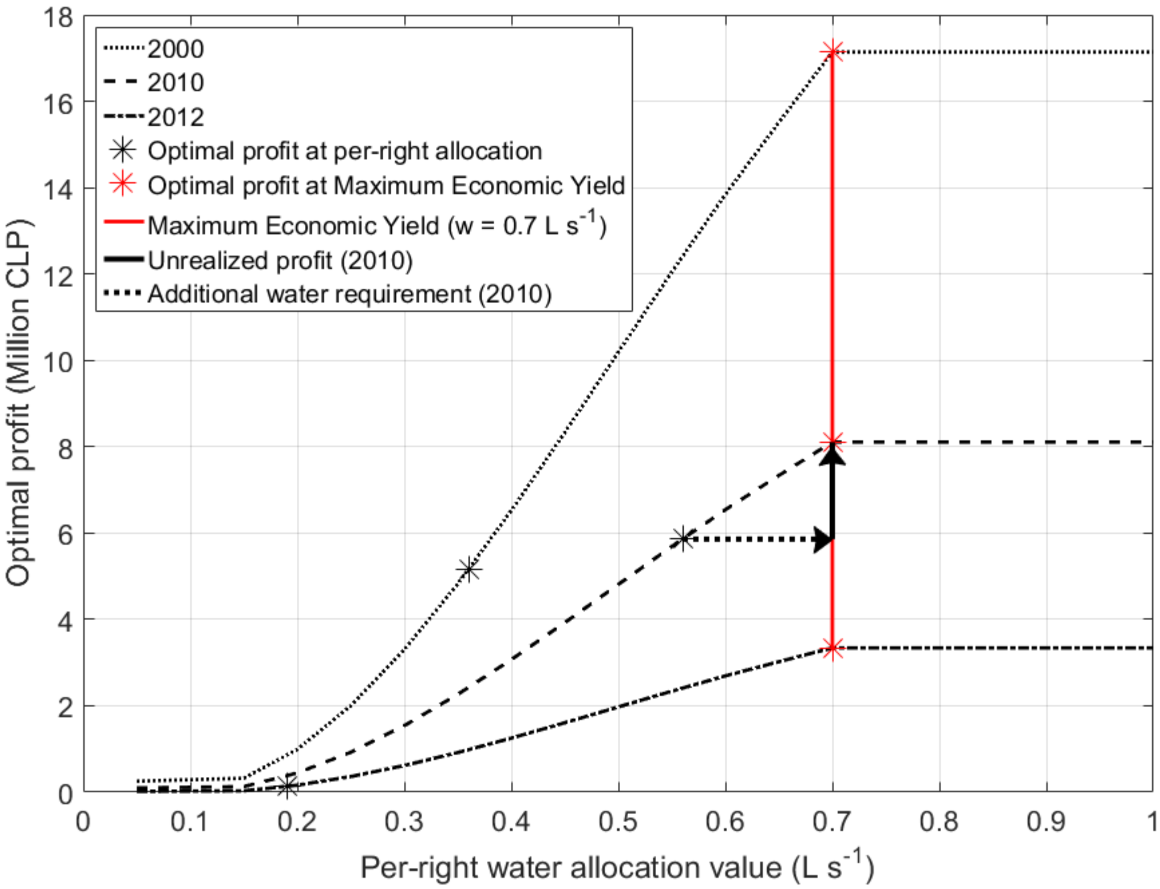


Figure 4. Optimal grape profit frontiers (Maximum Economic Yield achieved at Crop Water Requirement) Each curve represents frontier of expected optimal expected **profit for all feasible per-water right allocation values.**

To achieve MEY expected profits, grape farmers must also optimize the flow of water procured in the water market during years of deficiency. The optimal procurement strategy is calculated as the horizontal distance between the observed annual per-right allocation value and the CWR. The efficient pathway to MEY expected profit, in terms of whole water rights, is simply the number of water rights required to reach the CWR given the value of the annual allocation. Viewed retrospectively over the simulation period, a farmer might choose to seek permanent transactions consistent with a level of risk tolerance, eliminating necessary leasing through the water market (Fig 5). A single water right per-hectare provides MEY profits for 20% of years between 2000 and 2015, while a second water right secures MEY profits for an additional 50% of the period of record. Not until seven rights are owned has a farmer obtained sufficient water to avoid temporary procurement in the market, for the 16 years evaluated. Holding seven water rights is suboptimal, and results in instances of surplus which the profit maximizing farmer should seek to sell.

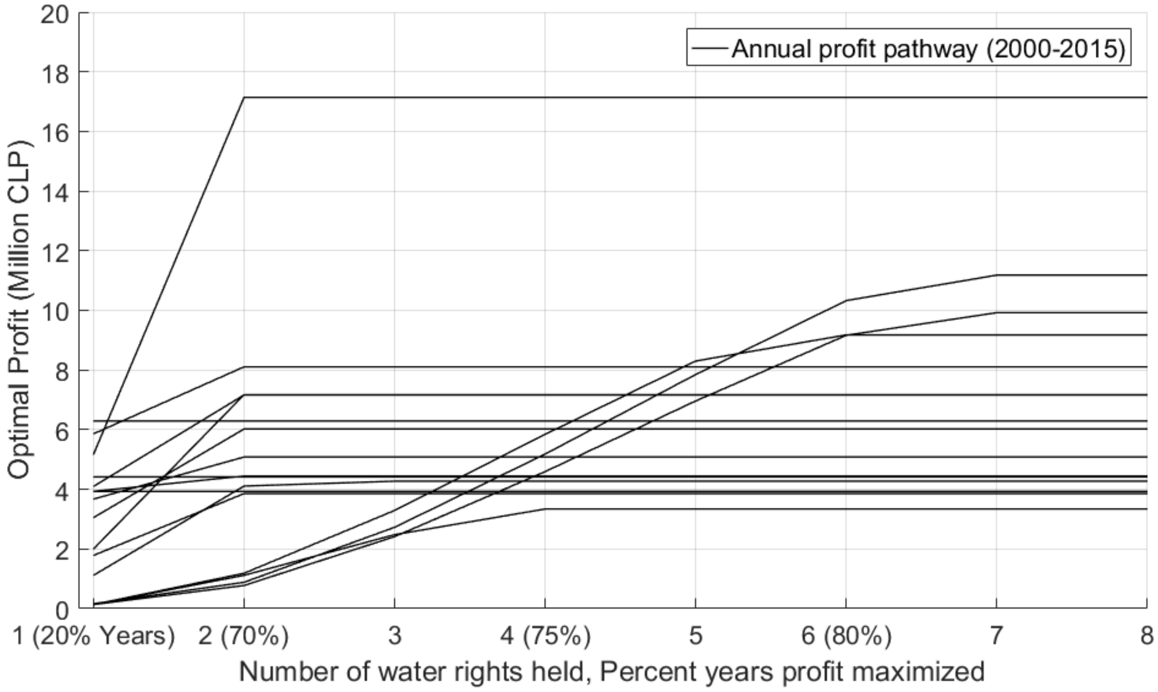


Figure 5. Optimal profits corresponding to number of water rights, and percent of historical years where number of rights sufficient to achieve maximum expected profit (2000-2015). Curves correspond to water rights ownership impact on expected annual profit.

Assesments of rights procurement strategy and corresponding potential expected profit gains are informative, but not sensitive to diminishing marginal utility of water tranformed to yield and ultimately to expected profit. That is, the difference between MEY expected profit and optimal expected profit for the actual per-right allocation is representative only of the potential gross gains from procuring water, and indicates nothing about the cost farmers should be willing to pay for the water. Establishing the utility of water in terms of per-right allocation (Fig. 6a) and demand (Fig. 6b) has the potential to provide farmers a more realistic estimate of the cost at which water should be procured. The utility of water, $U(w)$, exhibits an exponentially increasing trend (Eq 8), consistent with expected behavior (Griffin 2006). This suggests as the per-right allocation value increases, the profit potential (utility) increases.

$$U(w) \ = \ 2 \cdot 10^{7} w_{t}^{1.4752} \tag{8}$$

The demand schedule, $D(w)$, describes diminishing marginal utility and is defined by the negative second derivative of the utility function, $\partial^{2}U/\partial w^{2}$, and given by Equation 9 (Griffin 2006). The constant subtracted from the demand function constrains the price of water to be zero at the CWR. The area under the demand curve (Fig 6b) from the observed per-right allocation value to the CWR, is the TWTP for water required to achieve MEY profit on a per-hectare basis. Here, for the TWTP for water, as the observed allocation rises, the value farmers attach to water required to reach MEY decreases.

$$D(w) = \ -\frac{\partial U^{2}}{\partial w^{2}} = \frac{1.4 \cdot 10^{7}}{w_{t}^{0.52}} - 1.69 \cdot 10^{7} \tag{9}$$

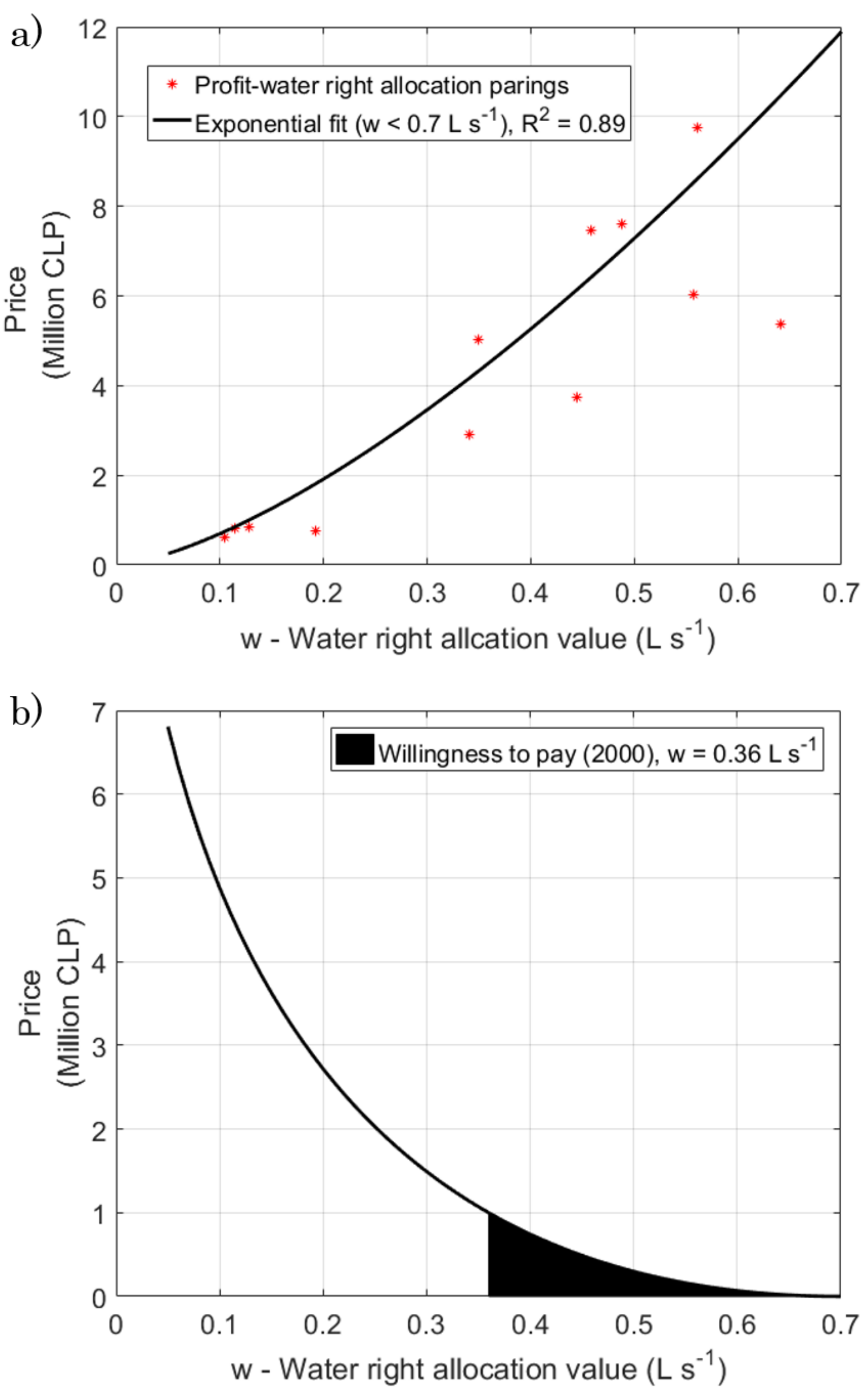


Figure 6. (a) Water right utility function, (b) Water demand

The range over which per-water right allocations result in measurable yields (0.05 liters per second - 1.0 liters per second) provides a lower bound at which the crop-water model indicates allocations result in vine kill (below 0.05 liters per second). Although observed allocation values never violate this threshold, and likely JVRE would work to provide at least the amount of water required to protect against vine kill, an analysis of grape farmer willingness to avoid vine kill is provided to describe the full range of the demand function.

Grape vineyard establishment costs include planting and maintenance, trellis system construction and installation, irrigation, fertilization, and pest management (Verdegaal, Sumner, and Murdock 2016). Marketable yields are not expected for the first two growing seasons after planting, and in the third year 5 tons per acre is expected before full production is anticipated. Utilizing an annual discount rate of 2%, and accounting for foregone mean annual yields (11.76 metric tons per hectare: 2000-2015), grape farmer willingness to avoid a single vine kill event (net allocation less than 0.05 liters per second) is 24.2 million CLP. Thus, the full extent of the demand function is revealed (Fig 7).

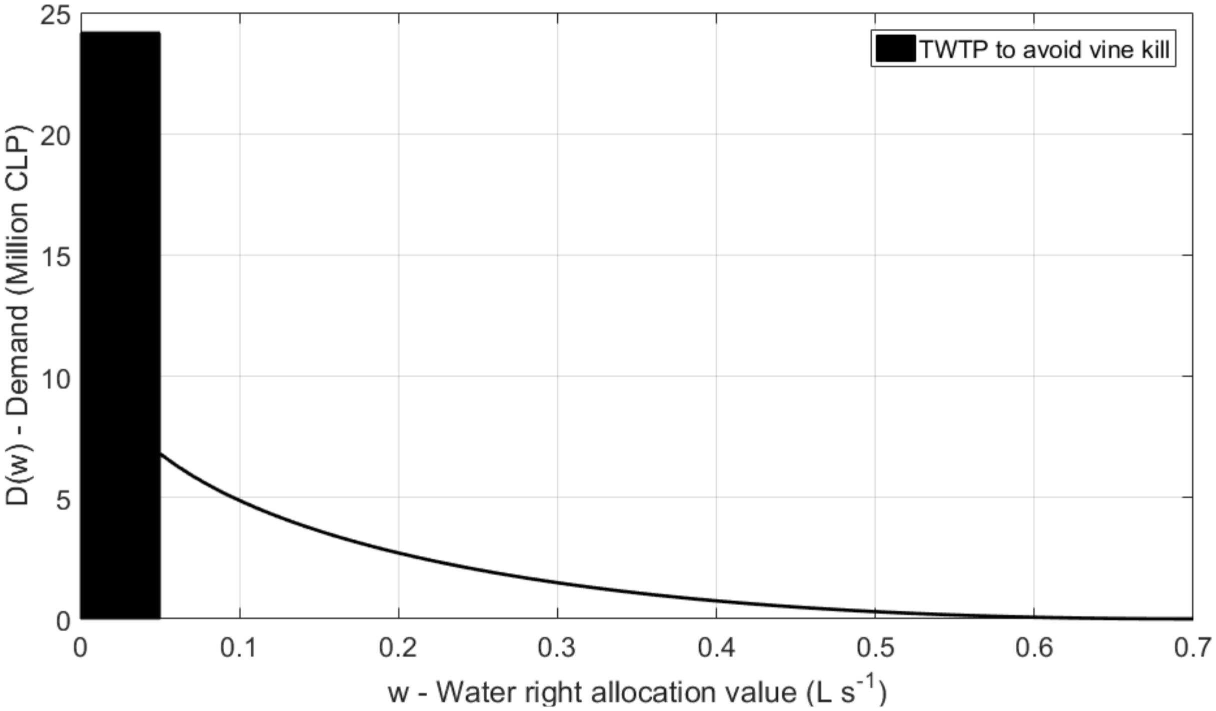


Figure 7: Grape water demand including total willingness to pay (TWTP) to avoid vine kill

3.3 Analysis of rights owner expected profitability

An important variable in production, which is relatively unknown in the Elqui Valley, is the distribution of rights among farmers. The difference in the number of water rights held per-hectare provides insight to farmer behavior, expected profit potential, and the requirement for market engagement. To investigate the degree to which different initial water rights ownership strategies have the potential to impact grape farmer decision making, two cases are developed:

1. A farmer owns one hectare for which a single water right is held, hereafter referred to as 1WR. This ownership strategy may represent a risk accepting farmer, willing to engage in the temporary water market when the per-right allocation value (historically at 0.5 L/s on average) is below what is required to maximize per hectare expected profit (Donoso 2006). 1WR farmers should expect frequent water market engagement to achieve MEY (Figure 5.)

2. A farmer owns one hectare for which 2.25 water rights are held, hereafter referred to as 2.25WR. The 2.25WR strategy is based on a uniform distribution of water rights to currently irrigated land area planted in grapes per (Zunino et al. 2009). This strategy represents risk aversion relative to the 1WR strategy, and it is expected these farmers will engage in market activity in less than 30% of years (Figure 5.)

In both cases, farmers are profit maximizing and engage in market activity in any year where per-right allocation and water rights ownership status result in a water deficit. It is assumed farmers seek only temporary water transfers through the market, and at the end of the year revert to their initial water right ownership status. Likewise, sufficient water is assumed available in the market such that farmers can procure enough to achieve MEY. However, a farmer only purchases water if the TWTP for the water (a function of potential increases in profit) is less than the point at which the cost of production exceeds profit, such that profit after market engagement must be exceed initial expected profit.

Evaluating water surplus and deficit, in terms of CWR, illustrates how initial rights holdings are affected by inter-annual variability and the relationship (correlation) between allocation and observed storage in Puclaro (Pearson Correlation

Coefficient = 0.76; Fig. 8a.) For the 1WR case, water deficit occurs in 13 of the 16 years, requiring market engagement to achieve MEY. In contrast, the 2.25WR scenario results in relative surplus, and market engagement is only required during a four-year period of the 2009-2015 drought. The largest deficits in both scenarios occur during the prolonged drought (2012-2015), when observed allocations were <0.20 liters per second (*personal communication*, JVRE).

To measure the effect procuring water at the TWTP has on profit, a baseline scenario in which no water market engagement occurs is evaluated. As expected, expected profits (Fig. 8b) for both the 1WR and 2.25WR cases are substantially reduced without market engagement (Fig 8c.) Aggregating across the 16 years on a per-hectare basis, for the 1WR case, 58% (66 million CLP) of MEY potential profit is foregone, while 26% (28 million CLP) is foregone for the 2.25WR case. The difference in optimal expected profit between 1WR and 2.25WR ($\sum_{t=2000}^{2015}(\pi^{*}_{2.25WR} - \pi^{*}_{1WR})$ is 37 million CLP, indicating farmers initially holding 2.25 water rights make substantially larger profits when both do not engage in the water market.

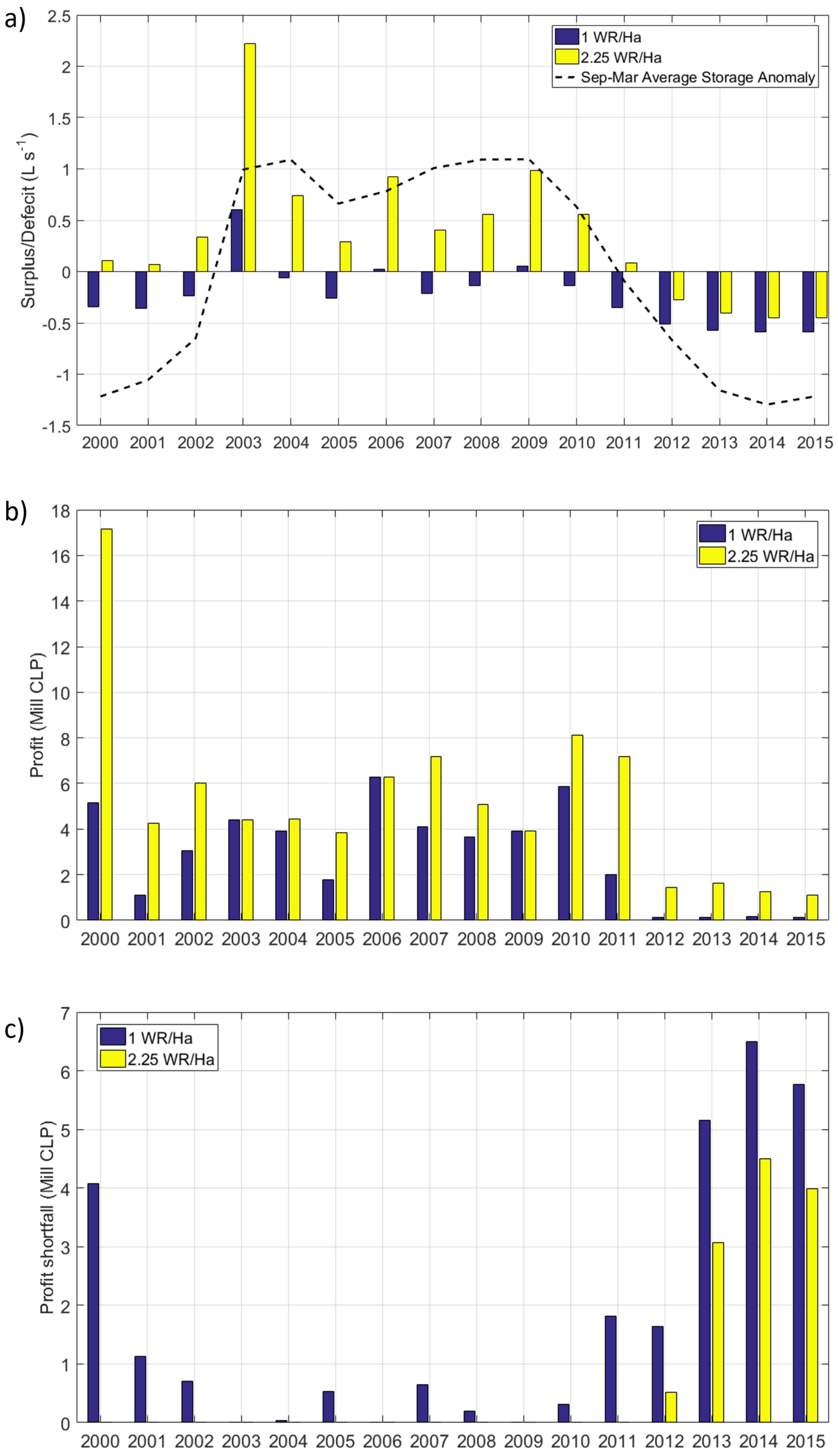
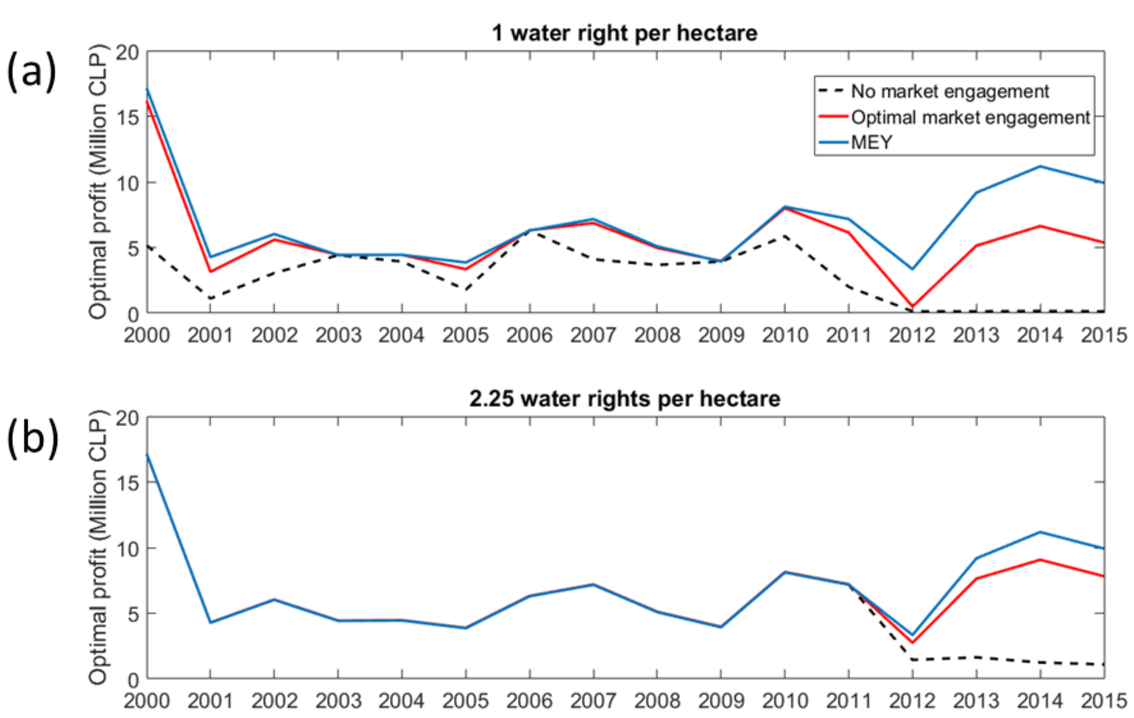

a)
Surplus/Defecit (L s^{-1})
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
1 WR/Ha
2.25 WR/Ha
Sep-Mar Average Storage Anomaly
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
b)
Profit (Mill CLP)
18
16
14
12
10
8
6
4
2
0
1 WR/Ha
2.25 WR/Ha
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
c)
Profit shortfall (Mill CLP)
7
6
5
4
3
2
1
0
1 WR/Ha
2.25 WR/Ha
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Figure 8. (a) Annual water surplus and deficit, (b) Expected profit at observed per-right allocation without market engagement, (c) Foregone profit due to no market engagement

If full market engagement is allowed, including temporarily buying and selling water rights annually, expected profit increases for both the 1WR and 2.25WR cases. For all years where the per-water right allocation value does not allow for MEY to be obtained without market engagement, the TWTP is less than the potential gains, which prompts trading. Expected profits post engagement are given by Equation 9 (see above), and shown by Figure 9 (a) & (b). Gains from market engagement are significant in both cases, with post market engagement optimal expected profit difference of 14.5 million CLP compared to 37 million CLP without market engagement, which suggests that there is both a benefit to market engagement, and that given adequate market supply, trading closes the expected profit gap between farmers with different rights holding strategies (Table 2). The analysis assumes an adequate supply of rights exists in the temporary market such that 1WR and 2.25WR holders would bargain and secure the optimal number of rights at the TWTP. Profits for 1WR nearly double, despite high TWTP costs in drought years (2009-2014). In 2012, the combined effect of the below average per-right allocation value (0.19 liters per second) and below average grape market prices (252 thousand CLP per metric ton) make profits gained by market engagement nearly equal the potential profit gains for the 1WR case. In contrast, for 2013-2015 the per-right allocation continues to decrease (0.12 liters per second average) while grape market prices rebound (637 thousand CLP per metric ton by 2015), which provides increased incentive to engage in the water market, resulting in nearly ten-fold increases in profit for both the 1WR and 2.25WR cases. The drastic difference between potential outcomes 2012 verses 2013-2015 suggests farmer decisions should be based on an agro-economic approach.


1 water right per hectare

2.25 water rights per hectare

Figure 9. Comparison of annual profit outcomes with and without market engagement for (a) one water right per-hectare, (b) 2.25 water rights per-hectare

Table 2. Comparison of profit outcomes with and without market engagement by grape farming water rights holders

Profit (Market Engagement) (Million CLP)	**1WR**	**2.25WR**
None	45.9	83.3
Optimal	91.0	105.5
Gains from market engagement (%)	98.3	26.6

4 Discussion

The model presented here couples grape yield response to water with profit maximization to determine optimal behavior under observed and maximum economic yield (MEY) producing allocations, both with and without market engagement. The analysis indicates that for the period 2000-2015, optimal market engagement by farmers holding 1 and 2.25 water rights per-hectare could increase per-hectare profits by up to 98% (45 mill Chilean Pesos) and 27% (22 mill Chilean Pesos), respectively. Market engagement occurs when there is a positive difference between profit at MEY and profit at the allocation value, and when a farmer's total willingness to pay for the additional water is less than the difference. Further, an assessment of initial water rights ownership and profit potential illustrates how farmers might act to secure permanent rights to manage the degree to which they engage in the temporary market. Over the period evaluated, rights holders with a single right can expect to engage in market activity in 80% of years; increasing ownership to two rights requires farmers to engage during 30% of years, and with seven rights market engagement is avoided completely.

The analysis reveals a water price negotiation space available to grape farmers, where there is a demand-based incentive to enter the water market in any year where the per-right allocation and initial rights ownership combination result in yields below MEY. Calculating the annual difference between profit achieved with MEY and profit at the per-water right allocation value equips the farmer with a profit and cost sensitive estimate of the fair market value, or total willingness to pay (TWTP) for a water right used as an input to grape production. The TWTP, derived from the demand function, represents an upper bound of the fair market value of water and allows the buyer to frame their negotiation space, or range of acceptable water prices. The negotiation space is thus the difference between water received free of charge and the TWTP. Thus, a grape farmer should be willing to pay any value within the negotiation space for the allocation of water which allows them to achieve MEY. Contrastingly, economic logic suggests farmers with excess water, or an initial endowment beyond the CWR, have no incentive to retain it. Applying excess irrigation to grapes in exceedance of the crop water requirement (CWR) is wasteful and has the potential to damage the crop. Thus, the marginal benefit of water beyond the CWR is zero, and theoretically, excess water could be relinquished without cost. However, market activity indicates sales of excess water do occur where at least two growers competitively seek water. The price for which excess water should be sold is not addressed here and can be investigated to further analyze optimal market engagement, modelling water rights holders as a buyer or seller, dependent upon the year and climate condition.

Farmers holding a single water right should seek to engage in market activity each year (2000-2015) due to the fact input costs (fertilizer, labor, and fees), even at their highest 2000-2015 levels, are insignificant in comparison to the market price of grapes, and that yield is contingent upon water supplied to vines. The fact remains the Water Code of 1981 stipulates water rights initially be supplied free of cost, which alleviates water rights holders from paying the opportunity cost of water for another, perhaps superior, economic use. This is because DGA bestows water rights based on order of application, provided the use is deemed beneficial, and is not permitted to bestow water rights to the applicant with the greatest expected economic use. In addition, water rights applicants do not necessarily consider the opportunity cost of their chosen use at the basin scale. That is, a farmer's intended use may not represent the best economic use. A two-firm economic equilibrium model may be used to determine the economically efficient distribution of water and its accompanying price. A two-firm model requires identification and demand derivation for at least a second crop type farmer, so the potential for water trades may be addressed. This is possible using the framework constructed here.

Given a mean seasonal allocation (2000-2015) of 0.36 liters per second, with the independent assumption that rights are uniformly distributed among hectares planted in grapes (Zunino et al. 2009), which is embodied by the 2.25WR case, the corresponding mean per-hectare allocation is 0.81 liters per second. This suggests farmers are responding to continuously below normal allocations, by permanently buying rights which ensure that for all but the worst drought years, MEY is reached. This is evident in the model results as shown by Figure 8 (b.) Still, the purported vigor of temporary transactions in the water market suggests some water rights holders have either chosen or are not able to secure permanent rights which protect against drought. These are likely to be farmers of smaller vineyards, holding fewer water rights per-hectare than average, and those unable to purchase permanent rights, which have become increasingly costly to procure (de la Luz Domper 2009). Although observed allocations never fall below the vine kill threshold (<0.05 liters per second) a net present value calculation reveals per-hectare replacement costs to be between 20% (2.25 water rights per-hectare) and 53% (1 water rights per-hectare) of the sum of corresponding profits over the period analyzed. This result suggests grape farmers have a strong economic incentive to avoid vine kill, as the expected cost of vine replacement is roughly 3.5 times greater than largest willingness to pay for allocations resulting in productive yields.

The work presented here is focused only establishing a comprehensive demand derivation framework for temporary water markets. As such, we assume rights availability in the market to be sufficient to meet annual demands of grape farmers—no supply constraints or two-firm analysis, described above, are performed here. Assuming each farmer in the basin, across all crop types seeks to meet their crop's CWR, there exists the possibility for rights supply and demand inequality in a competitive water market. In the Elqui, [*Hearne and Easter*, 1997] report that ESSCO, the private company responsible for water supply in the Elqui Valley's populous coastal region, is expected to hold more than 2,000 uninterruptible water rights by 2018, which are not considered tradable. A uniform distribution of 8,000 water rights among hectares planted in grapes in the Elqui (Zunino et al. 2009) suggests that roughly 15,000 rights are dedicated to other types of agriculture and other minority uses. Based on the assumed number of potentially tradable rights (~23,000), and the feasible range of annual, per-water right allocation values, instances of both excess and insufficient supply may occur. Additional research is required to investigate how farmers of different crop types (perennial vs. annual, high vs. low value) might interact such that profits are optimized on a basin scale, and how rights supply and demand inequality affect basin-scale economic outcomes.

Farmers are assumed to have a priori knowledge (prices, fertilizer and labor requirements), or equivalently perfect information. A season-ahead forecast of per-right allocation values, market prices, and inputs could allow farmers to make early cropping and water market decisions. Presumably, the market price of water varies throughout the austral Winter and Spring, prior to the date (September 1st) JVRE sets the annual allocation value. However, once the allocation value is set, the market price should not vary and is given by the peak demand for water. Streamflow forecast models could benefit from the strong relationship with the El Nino Southern Oscillation in the Elqui, and market forecast model could draw on the relationship between USDA reported market price of grapes (Aug, Sep) and prior March Chilean harvest prices (Pearson Correlation Coefficient = 0.50). This warrants further investigation.

The treatment of farmer decision making used here is simplistic and highly stylized as to represent a basic allocation uncertainty coping strategy available to grape farmers. The agro-economic model component that simulates this, while perhaps logical, is only one of many ways farmer attitude toward risk can be formulated. Utilizing an alternative approach, like the von-Neumann-Morgenstern utility function, which holds farmers as risk averse and downside prudent, could be substituted in place of the maximization of expected profits model used here, and will likely produce different results. The decision model only permits grape farmers to engage in temporary allocation transactions. Realistically, economically rational farmers would consider both the expected present value of a permanent transaction and the expected annual value of temporary transfers, choosing the option which holds greater value. In addition, the decision model requires farmers to seek transfers that span the entire growing season. In the Elqui Valley, temporary transfers can occur in many temporal configurations, both in terms of flow and quantity, to supplement flow as required. Additional research is required to address these limitations.

The ability to explicitly verify and validate the model is currently limited for the Elqui Valley. For a full validation, candidate farms should be identified, with historical yields, water rights holding, and area cultivated provided. ODEPA only tracks yield at the regional scale (Coquimbo contains three provinces: Elqui, Limari, and Choapa). Aggregated yield is reported, and only for table grapes, and only 2015. In its Fruit Land - Principal Results report, published in July 2015, ODEPA reports per-hectare yields of 14.35 metric tons. This result is within the range of yields produced by the crop-water model, which suggests the model is calibrated appropriately. In addition, yields calculated by the crop-water model do fluctuate temporally, as expected, in response to the observed per-water right allocation value. It is not appropriate to downscale this result to the Elqui Valley without knowing the production of the remaining provinces in the region. It does suggest, however, that grape farmers are likely overcoming low per-water right allocation values to produce substantial yields (83% of AquaCrop yield at CWR). We postulate these results are achieved through the procurement of a sufficient number of water rights, either permanently, or temporarily, which motivates this research

While validation is difficult, the stability of the economic model can be evaluated by reformulation using observed production input and market prices, to identify which parameters the model is most sensitive. This is achieved by maximizing minimum benefits and maximizing maximum costs over the retrospective period, which results in a minimization of expected profit. The expected maximized minimum per-hectare yield gross revenue is 4.4 mill Chilean Pesos and occurs in 2012. The maximized expected cost of production inputs on a per-hectare basis is 127 thousand Chilean Pesos in 2015, 606 thousand Chilean Pesos in 2011, and 46 thousand Chilean Pesos in 2015, for labor, fertilizer and water user association fees, respectively. Thus, resultant expected profit is 3.6 mill Chilean Pesos, which is only 186 thousand (4.8%) less than the 2012 maximum expected profit (smallest maximized profit 2000-2015). This result illustrates that the market price of grapes is the dominant feature in production, even in the most profit limiting case constructible using observed price information. Fertilizer is two to 12.5 times more expensive than labor and five to 31 times more expensive than fees in corresponding years for maximized values of each. Thus, it is evident that fertilizer has the largest influence over expected benefits. Yet, the cost of maximized fertilizer use is 2% to 11% of corresponding annual yield, which further illustrates the degree to which farmer decisions are market price driven, as the model is formulated. In addition, the allocation in 2012, while below average (0.19 liters per second, $\mu = 0.47$ liters per second), is still larger than the allocation in the following three years by 46%, 72% and 90%. The grape market prices in these same years are 231%, 276%, and 248% larger than 2012. The effects of market price and allocation value on TWTP and expected profit from engagement during this period (2012-2015) are best illustrated by Figure 8, noting specifically the difference in magnitude between expected benefits from optimal market engagement (red line) and no market engagement (dashed black line). In 2012, the difference is much smaller than it is in any of the following three years, which suggests that even though the per water right allocation values continue to fall from 0.19 liters per second in 2012 to 0.10 liters per second in 2015, which in turn, results in corresponding growth in TWTP, it is the market price of the grapes that is driving the magnitude of the difference between expected profit under optimal engagement and expected profit under no engagement.

5 Conclusions

Water rights have developed as a legal mechanism by which water scarcity is addressed through the establishment of limited access permits. Such is the case in the Elqui Valley of North Central, Chile, where water rights holders face uncertainty in terms of the allocation value of a right, which is set annually based on a combination of reservoir storage, expected inflow, and expected future conditions. Water rights are transferable (temporarily or permanently), which allows rights holders to further address allocation uncertainty by securing additional water. The farm-scale agro-economic modelling demand framework developed here uses the temporary transferability of water rights to describe how grape farmers may seek engage optimally in water markets such that their expected annual profits are maximized.

This work relies of the free-market economic basis of the Water Code to guide the selection of framework components. The result is an innovative demand derivation framework which produces water price and quantity signals farmers may choose to incorporate in their agricultural decision-making, thereby encouraging economically driven behavior within the constraints of the existing law. Thus, policy implications are rightfully targeted to the water right holder rather than the Water Code and the accompanying institutional arrangements. The broader insights of the research can be summarized:

1) Informal temporary water markets constructed on neo-liberal economic principles lack a price revealing mechanism. The coupled crop-water, agro-economic approach allows for the establishment of a price negation space and quantity farmers should seek in the temporary market. This basic structure may be adapted to different crops, crop models and economic models. Because all basins in Chile are subject to the Water Code, and temporary markets are largely informal, the framework may be applied most directly. The framework may also be applicable to regions where similar temporary water markets exist (e.g. Mexico, Australia and New Zealand; (Tietenberg 2002; Bjornlund and McKay 2002; Bjornlund 2003). Further applications may be made where water law and associated markets are emerging, as the Water Code has been presented by global development agencies as a positive model. Water managers in these regions must decide the economic basis upon which transactions can occur. The framework proposed here could be used to guide the level of temporary market formality, such that the inefficiencies associated with the informality of temporary markets in Chile can be avoided.
2) Risk attitude is a well-studied topic, and there are many ways to model economic agents. The framework presented here treats the farmer simply as a profit maximizer and provides profit and interaction information for varied water rights ownership strategies. This allows the farmer to adopt the ownership and interaction strategy that aligns with their risk tolerance, rather than specifying a single, optimal policy.
3) The framework reveals that in locations where rights holders can accurately assess the value of water in terms of its utility, optimal market engagement strategies can be developed which can add to farm-scale profitability, and act as an assessment of whether existing rights ownership matches farmer risk tolerance.

Farmers reliant on centrally managed water allocations as a means of obtaining adequate water supplies to irrigate crops face endogenous and exogenous uncertainties, including hydrology and water allocation decision-making. Optimal farm-scale water resource decision-making requires water rights holders to engage in permanent and/or temporary water transactions to hedge against these uncertainties. The decision-making strategies proposed here presents a process by which water rights holders engaged in agriculture may make informed water market engagement decisions with limited information to maximize annual profits. Implementation of the approach presented here by rights holders suggests improved economic efficiency for basins where water rights markets exist is possible.

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