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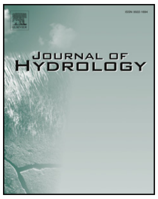

Research papers

Cooperative water trade as a hedge against scarcity: Accounting for risk attitudes in the uptake of forecast-informed water option contracts

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ABSTRACT

Season-ahead hydrologic forecasts hold the potential to inform water user decision making, provided forecast information offers value to targeted end-users, particularly in water-scarce regions. Yet, user willingness to trust forecast information is uncertain and often varied across similar user groups. Here, forecast uptake by agriculture users in semi-arid water rights managed basins is modelled to account for heterogeneous risk attitude and hydrologic variability. A season-ahead forecast of reservoir inflow is translated to water-trading rulesets through coupled reservoir allocation, i.e. per-water right allocation from the reservoir, crop-water, economic optimization, and demand derivation models. Theoretical growers, aligned in crop-type cooperatives, are modelled as potential exclusive water trading partners that, in years of scarcity may choose between forecast-informed water trading via option contracts, or one of two alternative water trade actions: persistence forecast-informed trading or no trading. Simulations across varied initial water rights endowment and farmer risk attitude allows for evaluation of expected investment of water rights in forecast-informed water trade. Results indicate farmer willingness to trust forecast information and subsequently invest rights option contracts trade is variable (28%–70%), and dependent on initial endowment of rights and alternative water trade action, manifested here as persistence-informed trade and no trade alternative. While variable, investment outcomes for probabilistic hydrologic simulations reveal long-term trade stability under nearly every forecast-informed water trading simulation, suggesting options contracts may be viable under a variety of water scarcity conditions. A key insight is that seasonal climate forecasts may prove to be quite valuable when translated through sectoral models, providing the tailored information to end users with diverse risk attitudes. This reinforces the potential in including forecasts in agricultural water resources decision support frameworks, as a hedge against water scarcity for farmers of varied earning potential.

1. Introduction

Water option contracts (OCs) have been implemented as a market-based approach to drought mitigation and transaction cost reduction for agricultural producers (Brown and Carriquiry, 2007; Wheeler et al., 2013; Vicuña et al., 2018). OCs provide a hedge against future market uncertainty, allowing prospective sellers and buyers to negotiate price and quantity terms for a good, which is valid at a later date. As a financial instrument, the value of OCs is clear when the contract quantity, or allocation, of water can be guaranteed by the seller. However, in many regions, allocations provided to water rights holders are uncertain and based on water availability (i.e. reservoir storage). As such, OCs have been deemed infeasible, and are not implemented (Vicuña et al., 2011; Vicuña et al., 2018). Where season-ahead forecasts of allocation can be produced with consistent skill, it is possible to couple forecasts with financial instruments, including OCs (Roncoli et al., 2009; Block, 2011; Delorit and Block, 2018). Likely benefactors of forecast-informed OCs, including farmers who make investment decisions ahead of planting, must determine whether forecast information holds sufficient value before they will integrate it in their decision making (Rey et al., 2016; Vicuña et al., 2018).

Assessing forecast option value is complex and should account for variability in both hydrology and target end-user group behavior (i.e. willingness to trust forecast information). With respect to hydrologic variability, prospective users of forecast-informed OCs are most likely to value products which are robust to many possible hydrologic conditions including prolonged and disconnected drought scenarios (Herman et al., 2015; Brown and Carriquiry, 2007; Adamson et al., 2017; Herman et al., 2016; Zeff et al., 2014; Soares et al., 2018). Resampling, bootstrap, and other statistical hydrologic simulation

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techniques have been used extensively to create ensembles of synthetic timeseries, with which the efficacy of OCs and other interventions may be assessed.

Second, option value does not accrue uniformly across water users. Willingness to trust forecast information is tied to farmer economic profitability (i.e. crop choice) and risk attitude, and therefore option value is variable both within and across sectoral water uses (Binswanger, 1980; Ziervogel, 2004; Tanaka et al., 2006; Tanaka et al., 2010; de Brauw and Eozenou, 2014).

Lastly, the option value of forecast information is variable to the benchmarks against which it is compared (Murphy, 1992; Mason and Stephenson, 2008; Pappenberger et al., 2015). Season-ahead allocation forecasts applied to OCs must therefore be compared to relevant alternative water transfer strategies and climate forecast information farmers may use, in unison, to cope with allocation uncertainty (Hansen et al., 2006; Rey et al., 2016).

An assessment of the option value of forecast-informed OCs should test the robustness of its performance to these relevant aspects to determine how, and to what extent, farmers may implement forecast-informed water decision-making through time. This type of analysis may provide insight to policymakers and those tasked with developing forecast-based financial instruments (Mortensen and Block, 2018).

Studies which assess farmer risk attitudes and willingness to adopt forecast-informed decision making generally take either theoretical (economic) or applied (behavioral science and economic) approaches. Theoretical approaches for eliciting farmer risk attitudes are rooted in choice economic theory and use expected utility or direct elicitation of utility functions (Bard and Barry, 2001; Rey et al., 2016; Adamson et al., 2017; Dozier et al., 2017; Kosovac et al., 2017). These are often criticized as abstracting from realistic conditions, particularly with respect to accurate measurement and alignment of utility functions with observations or assumed (often homogenously risk averse and downside prudent) farmer risk attitude (Carpentier et al., 2015; Ward and Singh, 2015; Gómez-Limón, et al., 2016).

Further, very few theoretical economic studies apply season-ahead forecasts, and instead use historical hydrologic conditions. When forward looking, these studies rely on projections of decadal to multidecadal hydrologic trends to evaluate models while ignoring the impacts of interannual hydrologic variability (Calatrava and Garrido, 2005; Kasprzyk et al., 2012; Molinos-Senante et al., 2016). In this way they are limited in their application to farmers as planting decisions may change year-to-year based on expected hydrologic and market (crop and production inputs) conditions.

Opposingly, applied approaches use field experiments which generally rely on farmer response to surveys (Roe, 2003; Bougherara and Gassmann, 2011; de Brauw and Eozenou, 2014). In contrast to theoretical approaches, applied approaches find that farmer communities possess a spectrum of risk attitudes, variable across region, type of agriculture, and production goal (Roe, 2003; Ziervogel et al., 2005; Qasim, 2012; Kosovac et al., 2017). Typically, farmer populations are categorized in groups by risk attitude (e.g. high, medium, low).

Unlike theoretical approaches, some applied studies address facets of farmer willingness to accept hydrologic forecasts at the seasonal scale (Ziervogel, 2004; Ziervogel et al., 2005; Bharwani et al., 2005; Wossen et al., 2015; Berger et al., 2017). These studies investigate uptake at forecast skill thresholds and seek to understand farmer-farmer interactions and forecast perception. These studies are beneficial in that they address heterogeneous farmer risk attitude by establishing subgroups based on risk tolerance but are limited in terms of their broader applicability. They are predominantly set in developing countries (Lesotho for Ziervogel et al. (2005); Limpopo, South Africa for Bharwani et al. (2005); Ghana for Wossen et al. (2015); Ethiopia for Berger et al. (2017), assess mainly rainfed agriculture, and are tailored to small-share subsistence farming and do not explicitly address the potential for mutually beneficial interaction between farmers as water trade partners.

The gap present in the applied approaches is how seasonal forecasts can be translated and implemented in large-scale irrigated agriculture in developed countries, which is an important and growing contributor to global food production (Siebert et al., 2005; Assouline et al., 2015; Food and Agriculture Organization (FAO), 2016). In many cases irrigated agriculture is required due to a mismatch between the growing season and peak precipitation timing (Delorit et al., 2019). Where seasonal mismatches occur, often strong water law emerges. In these regions, sustainable surface and groundwater resource management is sought, while provisions for fair access to water for economic use are made (e.g. agricultural production; (Bjornlund and McKay, 2002; Townsend and Adams, 2016; Wheeler et al., 2013).

Water law establishes surface water rights as limited access permits to some fixed or variable quantity water (Getches et al., 2015). Some water law and accompanying water rights systems are based on free-market economic approaches which allow rights to be transferred between users (Endo et al., 2018). Although water law varies by region, the economic basis of water law-types with tradeable rights are anchored by the Coase Theorem (Freebairn and Quiggin, 2006; Chikozho and Kujinga, 2017; Hasselman and Stoker, 2017). This approach suggests that through trading of water rights (temporary or permanent), water will be put to its best economic use (Coase, 1937; Ruml, 2005).

Where tradeable water rights are predominantly engaged in irrigated agriculture, forecasts may be tailored such that they are attractive to water rights holders and may be implemented without significant institutional change (i.e. fundamental shifts in water law). As land dedicated to irrigated agriculture continues to become a relevant piece of the global agricultural tapestry, investigating methods to implement robust, forecast-informed decision making to promote economic water use efficiency and bolster production in the face of hydrologic uncertainty will be necessary (Assouline et al., 2015).

The work presented here addresses the need to model hydrologically and risk-robust forecast-informed decision making in irrigated agriculture by utilizing beneficial components of both theoretical and applied approaches to risk. It applies a three-tiered heterogeneous risk attitude construct to theoretical high (HV) and low value (LV) farmers who consider formation of crop-type cooperatives that may engage in exclusive water trade under varied hydrologic conditions. The cooperatives are presented forecast-informed OCs as an alternative to persistence-informed OC water trade or no-trading approach (Delorit and Block, 2019).

The framework presented here is evaluated retrospectively (2000–2015) in the agriculture dominated Elqui Valley of North Central, Chile. The framework is suitable for broader application given that the water law and management of Chile is based on a free-market economic approach shared by other countries (Rieu-Clarke et al., 2017; Borgias and Bauer, 2017). Endo et al. (2018) perform an analysis of global water law and conclude that up to 58 countries, including Chile, have shared legal and economic attributes necessary to promote efficient, sustainable water markets. Here, only details essential to calibrating the framework are presented. Readers interested in additional detail on the case study are directed to Delorit, et al. (2019) and Delorit and Block (2019).

In the Elqui Valley, agricultural water users hold roughly 90 percent of the 25,000 fully allocated water rights assigned to the basin. The Chilean Water Code of 1981 (WC) stipulates that each water right is equivalently valued and does not exceed a 1.0 L per-second average, annually. However, it is possible, that during the growing season, allocation may exceed 1.0 L per-second. On September 1st, the privately held water resources management firm is tasked with setting the annual per-water right allocation value. Its decision is based largely on existing storage in a central reservoir and a mixed qualitative-quantitative assessment of expected reservoir inflow (Delorit et al., 2017). If storage and inflow are not sufficient to provide full (1.0 L per-second) allocations, each water right is curtailed proportionately. Coupled uncertainty in the allocation value and the date at which the annual per-

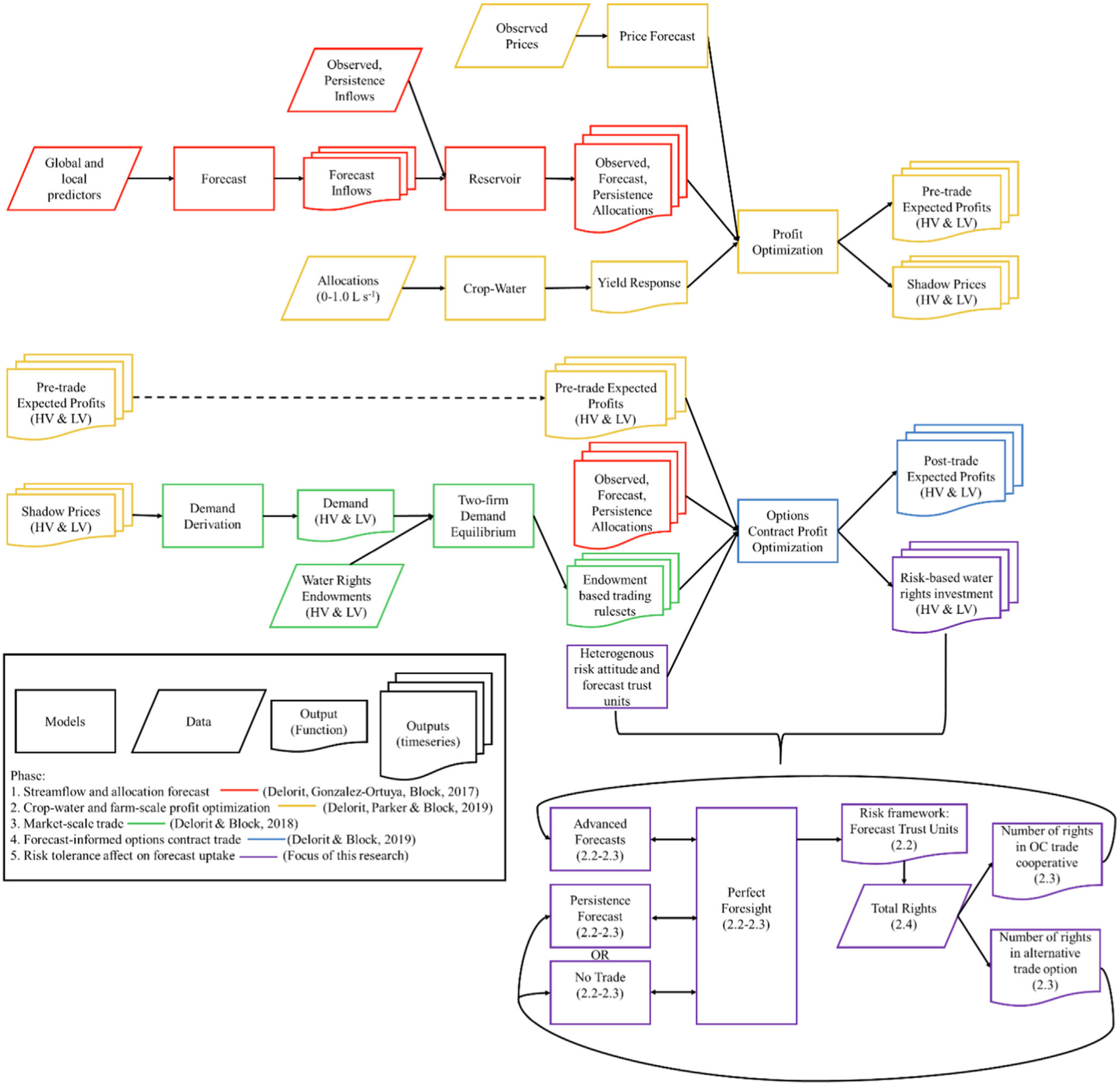

Fig. 1. Phased, per-water right allocation forecast production and translation framework. Note that colors correspond to framework phase. Components of Phase 5 include section number references.

right allocation value is set are present challenges for farmers in the Elqui.

2. Materials, methods and calculation

This work provides a novel framework to assess the robustness of forecast-informed options contracts (OCs) to variable hydrology and farmer willingness to trust forecast information in water rights-managed agricultural basins. Trust is manifested by the formation, size, and stability of high (HV) and low value (LV) growers' cooperatives that engage in exclusive water-trading to promote water market-scale economic benefits.

2.1. Forecast production and translation

The work presented here is an extension of several modelling phases (Fig. 1) designed to produce and translate season-ahead streamflow forecasts into information with which farmers can make consistently efficient water transfer decisions.

Phase 1 (Fig. 1, red components) addresses natural hydrologic uncertainty in the Elqui Valley. The primary growing season occurs from September to April, and many farmers must make production input decisions prior to the revealing of the annual allocation value (September 1st). Skillful season-ahead forecasts of growing season reservoir inflow are produced for the Elqui Valley for leads between May and August to provide advanced indications of likely allocation values (Delorit, et al., 2017). These forecasts are coupled with a reservoir allocation model which calculates annual per-water right allocation values. Hereafter, these forecasts are referred to as 'advanced statistical forecasts.'

Persistence allocations are defined as a 5-year running mean of allocation. For example, the per-water right persistence allocation for

2007 is the mean of observed annual allocation values for 2002 through 2006. Thus, persistence allocations *do* constitute a forecast, but one that is strictly based on recent historical observations. Hereafter, these forecasts are referred to as ‘persistence forecasts.’

Phase 2 (Fig. 1, yellow components) translates per-water right allocation values to expected yield and profit for representative crop-type cooperatives, on a per-hectare basis. Farmers may select to join a theoretical water-trading cooperative. Within the cooperative farmers are aligned by expected profitability, i.e. similar crop value. Alignment by crop value is necessary to ensure trading is economically beneficial, as trade vigor between equally profitable farmers would be low, as they share a comparable willingness to pay for water. The cooperative forms for the sole purpose of allowing members to benefit from water transfers. Individual cooperative members are permitted to produce and sell their yields as they deem necessary, like non-member farmers. Yield response to water is non-linear (Steduto et al., 2012; Liu et al., 2017) and calculated for the possible range of feasible per-water right allocation values (0.05–1.0 L per-second). AquaCrop, a crop-water model produced by the Food and Agricultural Organization of the United Nations, is utilized to simulate yield response to water right allocations (Geerts et al., 2009; Heng et al., 2009; Raes et al., 2009; Hunink and Droogers, 2010) to produce discrete pairings of allocation and expected yield (liters per-second, tons per-hectare). The continuous yield response functions are derived by regression, using yield and water right allocation parings obtained from AquaCrop, and are constraints in crop-type profit optimization. Regression of allocation onto yield provides derived yield response functions.

Market prices (CLP T^{-1}) are forecasted separately. The advanced statistical price forecast approach uses United States Department of Agriculture, 6-month lead, market prices of corresponding agricultural products to create a cross-validated, season-ahead regression-based time-series of expected prices in Chilean markets. The persistence-based forecast utilizes the same basic framework as the persistence allocation forecast, using the mean of three prior years.

Expected gross per-area profit (CLP Ha^{-1}) is calculated as the expected yield (T Ha^{-1}) for any allocation value multiplied by market price (as defined above) of the product; this is transformed to expected net profit when per-water right fees (maintenance, production inputs, etc.) are subtracted. Production inputs are modelled as constant returns to scale. Pre-trade expected profit and shadow prices for water are obtained. The underlying hydro-economic model used in this research phase presumes farmers are risk-neutral and profit maximizing. For additional detail, readers are directed to Delorit et al. (2019).

Phase 3 (Fig. 1, green components) illustrates how water’s shadow price for crops is used to derive each farmer groups’ demand for water. Simulating across many likely per-farmer water right endowment scenarios, a market-scale trade model is developed. Endowment describes the number of water rights held by a typical crop-type farmer. The model is based on a two-firm demand equilibrium model which specifies the economically efficient market price and net allocation distribution for each cooperative. The water-buying cooperative pays the equilibrium price to the selling cooperative, either until buyer demand is satisfied or until the supply of rights is exhausted. As such, supply and demand latency are possible. When allocations are low, competitive disequilibrium occurs. The threshold between equilibrium and disequilibrium is based on endowment of water rights. In disequilibrium, the marginal willingness to pay by the buyer exceeds the marginal willingness to accept of the seller, and negotiation is necessary to arrive at an economically efficient price (Griffin, 2006). Simulation across multiple endowment scenarios provides sets of demand-based trade rules by which the crop cooperatives agree to abide. For additional detail, readers are directed to Delorit and Block (2019).

Phase 4 (Fig. 1, blue components) amalgamates outputs from Phases 1 (allocations), 2 (expected profits), and 3 (endowment-based water trade rulesets), and simulates inter-cooperative water-trade using *option contracts*. Option contracts have been implemented in developed countries in basins where irrigated agriculture is a significant component of the water economy (Williamson et al., 2008; Ghosh and Willett, 2016; Marshall, 2016; Dozier et al., 2017). Applied here are several combinations of allocation and price forecast information to guide option contracts trading. Joint, per-cooperative, and per-water right expected surplus are generated for each combination and evaluated against a perfect foresight model informed with observations (*a priori* knowledge of allocation and price information).

Multi-stage forecasts of allocation are considered. Because allocation forecasts issued by the advanced statistical model are produced for several leads (May 1st–August 1st), option contracts pricing—a function of the demand-based trading ruleset—responds to forecast updates. Water’s strike price is the seller’s long-term expected value of the proportion of the per-water right allocation value suggested by the demand-based ruleset (Williamson et al., 2008). For each allocation forecast update (stage), the predicted market price of water and premium are calculated. The premium, which provides the buyer the right, but not the obligation, to purchase water is obtained using the Black-Scholes method (Black and Scholes, 1973; Black and Scholes, 1976; Sturm et al., 2017). At each stage, the buying farmer cooperative makes engagement decisions (e.g. to pay the contract premium or wait for the next stage) based on whether the market price of water is below the strike price. Ultimately, option contracts are ‘called’ if the revealed allocation value is insufficient to meet demand and the corresponding revealed market price is greater than the contract price secured when a premium is paid. For additional detail, readers are directed to Delorit and Block (2019).

2.2. *Risk attitude framework for developed countries*

The four-phase forecast production and translation model presented above, while novel, presume farmers possess uniform, neutral risk attitudes regarding water as an input to production. Further, they have only been evaluated over a single hydrologic forecast and set of observations (sequentially, 2000–2015). To remove the assumption of homogeneity and neutrality in risk attitude, and test inter-cooperative robustness to several hydrologic scenarios, the framework is expanded (Fig. 1, Phase 5).

2.2.1. *Farmers grouped by risk attitude*

Farmer risk attitude is dynamic and not necessarily uniformly distributed or skewed. The results of Ziervogel et al. (2005), Bharwani et al. (2005) and others, which apply heterogeneous risk attitude with respect to forecast trust, are tied to developing countries. Other studies identify trends in farmer risk attitude in developed countries (Roe, 2003; Roe et al., 2014). Roe et al. (2014) use an 11-point scale to elicit farmer risk attitudes working with commercial polling firms. Answers to questions are statistically significant, when controlled for confounding variables, in predicting observed risk behaviors like farm equipment and cropping investments and other high-risk choices (e.g. self-employment willingness; Jaeger et al., 2010; Dohmen et al., 2011; Roe et al., 2014). The results align respondents by risk tolerance (low = 26%, medium = 40%, and high = 34%). While risk attitudes among farmers in the Elqui Valley are unknown, the results of Roe et al. (2014) provide some indication of general attitude toward risk in developed countries and are used here to apportion Elqui farmers to three risk groups. This component of the framework is left purposefully simplified to allow for modification of both the number and distribution farmer population among risk groups.

2.2.2. *Forecast trust units (FTUs) as a measure of forecast option value: profit and alternatives*

Forecast trust units (FTU) are used to determine whether farmers will enter or leave the inter-cooperative water trade arrangement (partially following Ziervogel et al., 2005). FTUs accumulate with forecast accuracy over a specified period based on a comparison of

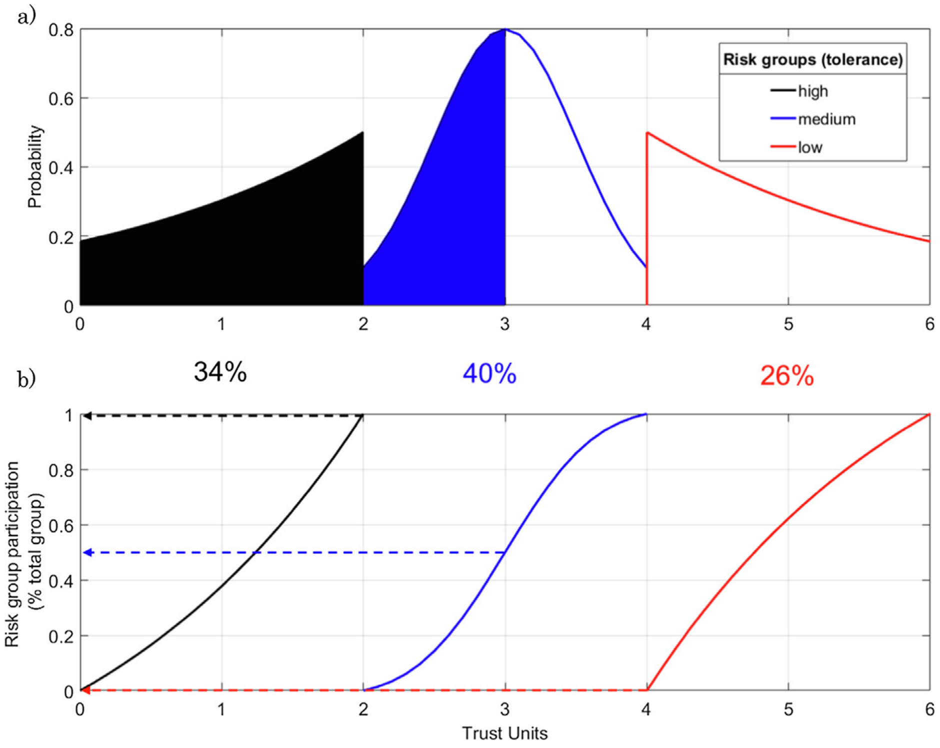

Fig. 2. Farmer risk group composition and Forecast Trust Unit (FTU) accumulation example (for 3 total FTUs): a) Distribution of farmer population to high, medium and low risk tolerance groups as a function of FTU accumulation. Percentages below the horizontal axis correspond to proportion of farmers from the cooperative in each risk group. b) Risk group-based aggregated willingness to participate in forecast-informed water trading. The dashed lines correspond to the proportion of each risk group willing to participate in forecast-informed OC water trade.

absolute profit differential (Eq. (1)). For every year expected profit from the advanced statistical forecast-informed model more closely matches the perfect foresight model than do the no trading or persistence forecast-informed model, an FTU is earned. If expected profit from the persistence forecast or no trading model is superior to the advanced statistical forecast, an FTU is lost (Eq. (1)):

$$FTU_M = \sum_{n=1}^{M} FTU_n = \begin{cases} 1, & |\pi_{obs_n} - \pi_{fcst_n}| < |\pi_{obs_n} - \pi_{pers_n OR notrade_n}| \\ & -1, \textit{otherwise} \end{cases} \tag{1}$$

where FTU_M is the sum of FTU_n for accumulation period M with years n; π_{obs_n} is expected profit from perfect foresight (observed) option contracts trading; π_{fcst_n} is expected profit given advanced statistical forecast option contracts trading; $\pi_{pers_n}$and $\pi_{notrade_n}$ are expected profit from persistence option contracts trading or no trading, respectively. Aggregating FTUs over a specified accumulation period determines entrance or departure from the inter-cooperative water-trading arrangement for the upcoming contract period. For FTU_M to be positive (water rights holders enter the inter-cooperative arrangement), advanced forecast performance must exceed that of a persistence or no trade alternative for the majority of years in accumulation period M.

Expected profits (π), calculated for the four sets described above, are analyzed in two ways to determine FTU accumulation in any period M:

1) **Joint surplus per-water right.** FTUs accumulate as a function of market-scale joint expected surplus. Total expected profit is divided by the total number of rights invested in the cooperatives, regardless of underlying ownership. This analysis reflects a case where the HV and LV farmers value collective action, trusting long-term gains will be made, and excess profit generated from trade will be equitably distributed between the cooperatives. Therefore, an equivalent number of FTUs accumulate between the cooperatives in M. Hereafter, this accumulation method is referred to as '**joint surplus**'.
2) **Per-cooperative, per-water right surplus.** FTUs accumulate based on market-scale, per-water right performance of each cooperative, and therefore may accumulate differently for the HV and LV cooperatives. This analysis reflects a case where FTUs accumulate based on whether farmers, within their own farmer crop-type cooperative, are better off, compared with joint performance. Hereafter, this accumulation method is referred to as '**individual surplus**'.

In the Elqui, temporary trading of water rights is possible along the entire extent of the river. However, the extent to which trading occurs between HV and LV farmers is likely low. This is due to the absence of a formal physical or virtual trading space and non-binding arbitrary trade restrictions imposed by local water communities (Delorit and Block, 2019; Delorit et al., 2019). Thus, a no trading alternative is considered. In addition, arrangements that use persistence forecast information might develop. This alternative reflects the widely accepted theory that innovation, manifested here as formation of water-trading cooperatives, drives competition (Petrakis et al., 2015; Bogdan, 2016). Thus, four distinct scenarios emerge – against which the advanced statistical forecast may be compared – namely by varying the mechanism by which farmers evaluate expected profitability (joint and individual surplus) and alternative actions (persistence forecast-informed options contract trading and no trading.) The following pairings of profitability-based FTU accumulation and alternative action emerge:

1) Joint surplus-based FTU accumulation – persistence forecast informed option contracts water-trading (**JP**)
2) Joint surplus-based FTU accumulation – no trading (**JN**)
3) Individual surplus-based FTU accumulation – persistence forecast informed option contracts water-trading (**IP**)
4) Individual surplus-based FTU accumulation – no trading (**IN**)

2.2.3. *Combining risk groups and forecast trust*

To fully develop the relationship between farmers and willingness to trust forecast information, it is necessary to describe the distribution of farmers within each risk group. This study follows the work of Bharwani et al. (2005), Ziervogel et al. (2005) and Roe et al. (2014). The high and low risk tolerance attitude groups, described in Section 2.2.1. The low risk tolerance group follows a 2-parameter lognormal distribution: Low $\sim$LN($\mu = 1$, $\sigma^2 = 2$), and the high risk tolerance group follows an inverse lognormal distribution, using the same parameters as the low risk tolerance group: High $\sim$LN($\mu = 1$, $\sigma^2 = 2$)$^{-1}$ (Fig. 2a). The inverse lognormal distribution attributed to high-risk tolerant farmers recognizes their need for some forecast skill to join the cooperative. For example, for a total FTU score of one during an accumulation period, approximately 30% of high risk-taking farmers are willing to join their crop-type cooperative (Fig. 2b). The remaining 70% of farmers in the high-risk group are unwilling to join until the FTU score is at least two. Farmers with medium (risk-neutral) attitudes are assumed to follow a 2-parameter normal distribution: Medium $\sim$N($\mu = 1$, $\sigma^2 = 0.5$). These distributions are simulated and likely not fully representative of the true distribution of risk attitude in the Elqui.

The proportion of HV and LV farmers willing to invest rights in forecast-informed option contracts trading is a combination of farmer risk groups and aggregated FTU scores (Eq. (2)):

$$V_{iN} = \begin{cases} [P_{i,h} \times F(FTU_M \leq 2)] \times V_{i\,tot} \\ [[P_{i,h}] + [P_{i,m} \times F(2 < FTU_M \leq 4)]] \times V_{i\,tot} \\ [[P_{i,h}] + [P_{i,m}] + [P_{i,l} \times F(4 < FTU_M \leq 6)]] \times V_{i\,tot} \end{cases} \tag{2}$$

where, V_{iN} is the volume of rights invested by cooperative i (HV or LV) in contract period N which follows FTU accumulation period M; $P_{i,h}$, $P_{i,m}$ and $P_{i,l}$ are the percentage participation from each cooperative group (high, medium and low risk tolerance). $F(FTU_M)$ is the proportion of the risk group distribution willing to trust forecasts based on the number of FTUs obtained in an accumulation period. $V_{i\,tot}$ is the total volume of rights held by the HV and LV farmer groups. Here, six total FTUs are required to achieve full rights investment (discussed below). V_{iN} is calculated based upon the number of FTUs accumulated over an accumulation period M. The proportions of farmers aligned with each FTU accumulation distribution follow the results of Roe et al. (2014): low = 26%, medium = 40%, and high = 34%.

An example may help to clarify: if the FTU score is equal to three, all high risk-taking farmers invest their water rights along with 50% of the medium risk-taking farmers (Fig. 2a & b). For $V_{i\,tot} = 100$, it follows that $V_{iN} = [[34\% \times 100\%] + [40\% \times 50\%] + [26\% \times 0\%]] \times 100 = 54$farmers.

2.3. Hydrologic simulations, forecast trust unit accumulation and contract periods

Hydrologic uncertainty in the Elqui Valley affects allocation values. The observed set of growing season allocation values (2000–2015) ranges between 0.2 and 1.3 L per-second (Fig. 3a). A prolonged hydrologic drought (2012–2015) forced reservoir managers to curtail per-water right allocations below the long-term mean of 0.46 L per-second Based on long-term observations for the Elqui (1950-present), this meteorological and hydrological drought is both the longest and driest on record (Delorit et al., 2017).

To test the robustness of inter-cooperative use of forecast-informed OCs, both prolonged drought transposition and random simulations are created from the existing allocation record (2000–2015). The prolonged drought is transposed to the beginning (Fig. 3b) and middle (Fig. 3c) of the period of evaluation (2000–2015) to gauge the effect of specified conditions. Additionally, 10,000 randomly generated simulations (sampling without replacement; Fig. 3d) are created.

Transposed drought and simulations match the length of observed allocation and market price data available for the Elqui (16-years). It is assumed that farmers who choose to join the inter-cooperative water-trading arrangement must commit their water rights for a period of 5 years. This allows for three accumulations periods followed by three contract periods (colored arrows and brackets, Fig. 3d):

> Spin-up: This is the first six years of the time-series during which farmers of prospective HV and LV cooperatives retrospectively evaluate expected profit (Accumulation Period $M = 1$). At the end of the period, farmers compare performance based on accumulated FTUs for: no trading ($\pi_{notraden}$), trading using persistence forecast-based option contracts (π_{pers_n}), and trading using advanced statistical forecast-informed option contracts (π_{fcst_n}) to facilitate trade. The total number of FTUs is between negative and positive six.
>
> Contract Period 1 ($N = 1$): This is the first five-year period of inter-cooperative water-trading. FTUs accumulated during the Spin-up period determine the number of water rights to be invested by each cooperative ($V_{HV_1}$and V_{LV_1}) during Contract Period 1 (Eq. (2); Fig. 3d). The four-phase model is used to calculate expected profits given the number of rights invested. FTUs accumulate during Contract Period 1 (FTU Accumulation Period $M = 2$).
>
> Contract Period 2 ($N = 2$): This is the second five-year period of inter-cooperative water-trading. The number of rights invested in Contract Period 2 is based on the FTUs accumulated during Contract Period 1 (FTU Accumulation Period $M = 2$). FTUs are reset to zero from the end of Contract Period 1 such that the water-trading arrangement is not unnecessarily buffered or penalized for previous performance.
>
> Contract Period ($N = 3$): Methodologically identical to prior steps, Contract Period 3 extends beyond the time-series shown (Fig. 3d) but illustrates how the water-trading arrangement would be expected to exist into the future.

Hereafter, FTU accumulation and contract periods are referred to as M or N, respectively. Because six FTUs are required to obtain the entire number of water rights available between the HV and LV cooperatives, i.e. all rights that could be invested are invested, and five FTUs is the maximum possible during $N = 2$ and $N = 3$, not all water rights can be invested in contract periods $M = 2$ and $M = 3$.

2.4. Water right endowment inequality

Unequal distribution of water rights, or hierarchically-based access to water, may affect farmer crop-type choices and profitability (Plunkett, Chaddad, and Cook, 2010; Hu et al., 2016). It follows that farmers with larger endowments of water rights may possess a comparative economic advantage over farmers with lower endowments, and thus may be able to influence water market interactions (Molinos-Senante et al., 2016). This may result in economic stratification in the agricultural component of the water market. In response, growers' cooperatives may form to provide farmers market leverage and the ability to collectively bargain water market pricing (Cook and Iliopoulos, 2000; Ortmann and King, 2007). The National Council of Farmer Cooperatives finds cooperatives emerge to do just this—provide bargaining power, establish access to competitive markets, competitively seek production inputs, promote profit-making, reduce, and manage risk. Cooperatives generally prioritize long-term economic resilience over short-term economic gains. In basins where irrigated agriculture is a meaningful component of the water economy, trading of water between growers' cooperatives may both improve basin economic efficiency (joint surplus) and mitigate per-water right allocation value uncertainty.

The market-scale analysis is facilitated by the formation of theoretical HV and LV cooperatives in the Elqui Valley, based on grape and potato farming. They are selected based on their importance to the agricultural economy, and representation of similar crop types. Grapes are representative of HV, perennial crop farmers who are believed to possess larger per-hectare endowments of water rights than LV, annual crop farmers.

True water rights ownership by HV and LV farmers is unknown. Thus, simulation over many potential water rights pools is necessary due to uncertainty in the true value. A uniform distribution of known water rights holdings along sections of the Elqui River reveal that HV farmers are expected to hold between 1.0 and 2.75 water rights on a per-hectare basis (Zunino et al., 2009). In contrast, LV farmers are

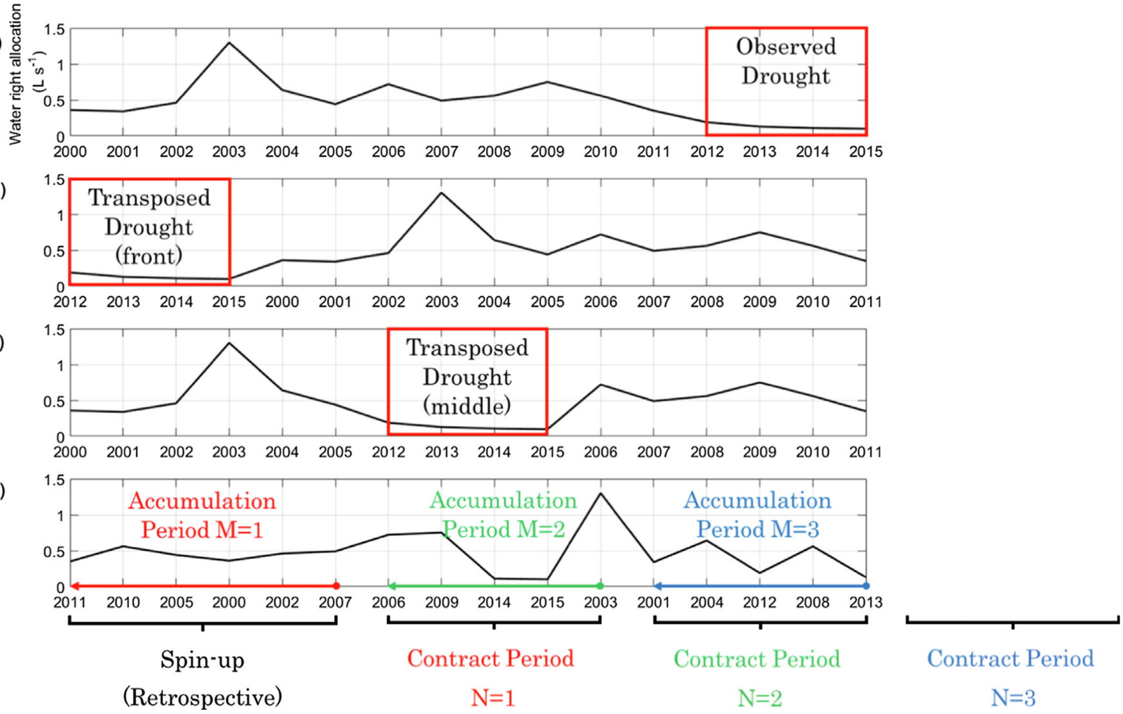

Fig. 3. Hydrologic simulations and corresponding Forecast Trust Unit (FTU) Accumulation Periods and water rights investment Contract Periods (shown for d) only): a) observed record (prolonged drought, 2012–2015), b & c) prolonged drought transposed to first four and middle four years, respectively, d) randomized hydrologic record (10,000 total simulations performed). Contract Periods are for five years and based on accumulation of FTUs in the preceding Contract Period or during Spin-up (applies to Contract Period 1 only).

believed to possess 0.58 water rights on a per-hectare basis (Venezian, 1987). Additional detail on basis-crop selection methodology and results is provided in Delorit, Parker, and Block (2019).

Based on these endowments, eight HV and LV rights ownership scenarios are developed. Each scenario is based on 0.25 water right increment changes in ownership by HV farmers (1.0–2.75 water rights per-hectare). The number of hectares farmed in HV crops is 3592 (Zunino et al., 2009). Thus, the number of water rights held by the HV farmers is the product of the eight, per-hectare endowments and the known number of hectares farmed. LV farmers are believed to farm 5,800 ha in any year (Zunino et al., 2009). Holding 0.58 water rights on a per-hectare basis equates to LV farmers hold 10,000 total water rights. The total number of water rights considered for the inter-cooperative water trading arrangement is 13,592–19,878 water rights (54%–80% of total water market share).

3. Results

3.1. Forecasts and expected profits

The coupled models provide insight to the potential utility of forecast-informed option contracts trading between the theoretical HV and LV water-trading growers' cooperatives (Fig. 4). In terms of per-water right allocation, the multi-stage advanced statistical forecast, issued on May 1st and updated on August 1st, correlates highly with observations (Pearson's coefficient of correlation (R) = 0.70, p = 0.002) (Fig. 4a). Categorical prediction (hit rate) of allocation values for three categories (moderate, severe, extreme), however, is only 53% (Delorit et al., 2017). This is well below the 60% to 70% categorical skill thresholds Ziervogel et al. (2005) and Bharwani et al. (2005) suggest are necessary for forecast uptake by end-users.

Comparatively, the persistence forecast (running average = 5-years) is highly dampened and tends to over-allocate during the observed drought (2012–2015). However, there are instances when the persistence forecast is significantly more skillful than the advanced statistical forecast (i.e. 2002 and 2008), specifically when allocations are near normal.

Advanced statistical market price forecasts, issued October 1st, are moderately correlated with observed Chilean market prices (R_{HV} = 0.50, p = 0.05; R_{LV} = 0.61, p = 0.01; Fig. 4b & c). The persistence market price forecasts do not correlate with observed market prices as well (R_{HV} = 0.13, p = 0.62 R_{LV} = 0.22, p = 0.40).

The sum of expected profits using advanced statistical forecast-informed option contracts to facilitate water trading over the period investigated (2000–2015) is clearly closer to perfect foresight than expected profit generated from either the persistence-informed option contracts or no trading alternatives (Fig. 5a) This is especially evident as the number of inter-cooperative water rights grows. In general, the persistence forecast produces optimistic expected profits, which are a function of over-allocation during the drought (Fig. 4a) The no trading alternative is inefficient because the water-trading rulesets, governed by demand, drives water from low to high value use.

Trading of rights is significant using the multi-stage advanced forecast informed option contracts across all endowment scenarios (Fig. 5b). The maximum number of rights that can be traded in any year is 10,000 (the total held by the LV group) For each endowment scenario, wholesale rights transfer from LV to HV occurs at least once across 2000–2015. Similarly, there is at least one year when allocations are sufficient to satisfy both HV and LV demand such that no trades are specified. As expected, the LV group is a majority seller (Fig. 5b: blue dot exceeds red dot) for all net endowments other than the largest (~19,900 water rights).

Persistence-informed option contracts rights trading is significantly lower than the multi-stage advanced forecast trading outcomes, across endowments (Fig. 5c). This result is a function of systematic over-allocation by the persistence forecast. In general, larger allocation values result in lower expected trade volume, and for many endowments (≥15,400 water rights) the HV farmer group is a majority seller. Persistence information also never results in trading outcomes greater than 6000 of the 10,000 possible rights.

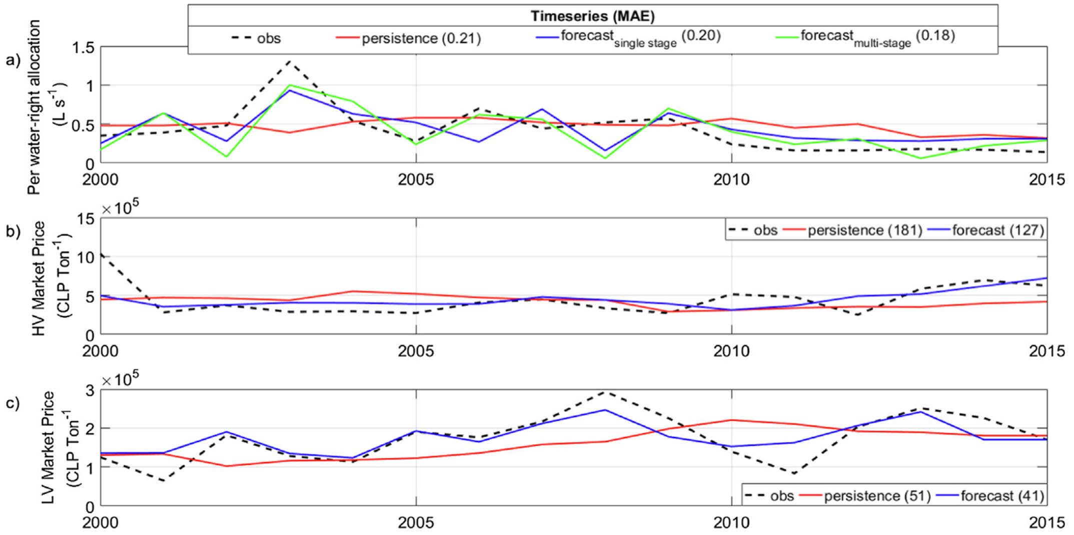

Fig. 4. Comparison of observed, forecast, and persistence: a) allocation, b) high value crop market price, c) low value crop market price outcomes. Mean absolute error (MAE) is calculated for each forecast approach.

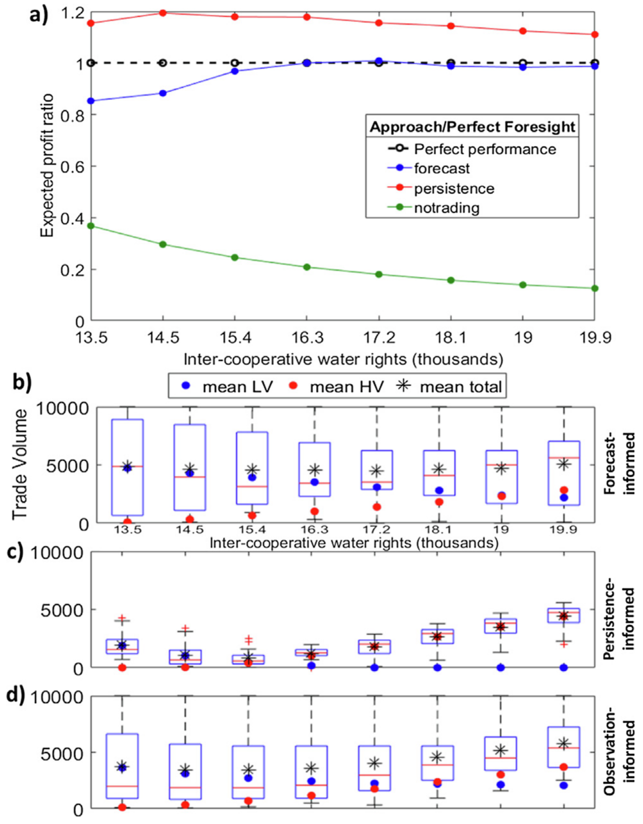

Fig. 5. Water right endowment-based expected outcomes (2000–2015): a) expected net profit ratios (approach: expected performance with observations), b, c, & d) rights traded using varied sources of hydrology and market price information.

Option contract water trading using perfect information (observations) suggests trading between HV and LV farmer groups should be vigorous across the endowment scenarios (Fig. 5d) Advanced forecast-informed trading (Fig. 5b) represents this expectation better than persistence forecast-informed trading (Fig. 5c). Perhaps of greatest importance is that both the prefect and advanced forecast models predict wholesale trade occurrences by the LV cooperative. The similarities and general alignment in outcomes of these two suggest that the advanced forecasts may hold value as trade information.

3.2. *Forecast trust units*

The preceding analysis is based on a single hydrologic simulation, assumes farmers as risk neutral, and all potential rights as invested in inter-cooperative water trading. That is, farmers are bound to participate in the water-trading arrangement. The heterogeneous risk attitude model removes these limitations by systematically revaluating farmer willingness to invest water rights in the water-trading cooperative using FTUs, while continuing to simulate over the range of likely inter-cooperative water rights ownership scenarios and alternative actions.

Total FTU accumulation difference between advanced forecast-informed option contracts water-trading and alternative actions (persistence and no trading) for each mode (joint or individual) across (2000–2015) illustrates clear positive trends, favoring the advanced approach. For scenarios where FTUs accumulate jointly between the HV and LV cooperatives, the value of the advanced forecasts differs significantly between the persistence (joint surplus – persistence forecast-informed options contract water trading (JP; Fig. 6a) and no trading (joint surplus – no trading (JN; Fig. 6b) alternative actions. For JP, the skill of the advanced forecasts applied to option contracts water-trading holds lower utility to HV and LV farmers, at each endowment scenario, as compared to JN. Additionally, FTU accumulation decreases with increasing total water rights endowments for the JP case. This occurs because increased water rights ownership means water is less scarce; the number of water rights owned by the inter-cooperative arrangement increases, but total irrigated land does not. Because persistence allocation forecast tends to over-allocate (Fig. 4a), and increased endowments buffer per-hectare allocations, the skill of the persistence forecast increases as endowments increase but remains less skillful than the advance forecast.

Alternatively, for the JN case (Fig. 6b), FTU accumulation increases as endowment increases. This increase can be attributed to increases in net allocation, which is the number of water rights held on a per-hectare average multiplied by the per-water right allocation value. Increased endowments imply more water available for trade, and thus the gap between gains from trade under the advanced forecast-informed option contracts and the no trading alternative grow.

In the cases of individual FTU accumulation by the HV and LV cooperatives, with persistence (IP; Fig. 6c) and no trading (IN; Fig. 6d) alternatives, the same basic outcome is observed: generally, fewer FTUs are accumulated in IP than IN. However, the relationship between HV

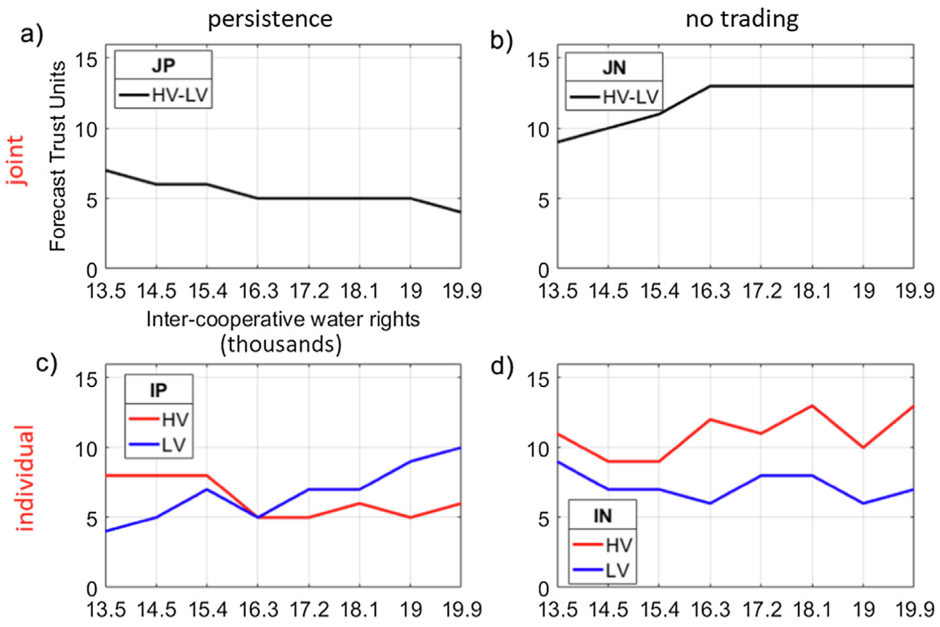

Fig. 6. Expected Forecast Trust Unit (FTU) accumulation for advanced forecast method minus persistence forecast (P) or no trading (N) for joint (J) and individual (I) profit cases: a) Joint surplus: advanced FTUs – persistence FTUs (JP), b) Joint surplus: advanced FTUs – no trading (JN), c) Individual surplus: advanced FTUs – persistence FTUs (IP), d) Individual surplus: advanced FTUs – no trading (IN).

and LV farmer willingness to invest in forecast-informed option contracts water-trading is starkly different.

In the case of IP (Fig. 6c), LV farmer FTU accumulation increases by a factor of two across the increasing range of endowments. This can be attributed to the fact that, while LV farmer endowments are held static across the endowment scenarios, water rights held by the HV cooperative increase. In terms of water scarcity, underlying scarcity for LV farmers is constant, while for HV farmers it decreases. Thus, an inverse FTU accumulation regime is expected for LV (positive) and HV (negative) farmers for increasing endowment scenarios.

In the case of IN (Fig. 6d) a different FTU accumulation regime is observed. Like the JN case (Fig. 6b), forecast-informed trading provides extensive benefits by simply moving water from low to high value use. However, because HV farmers hold a comparative economic advantage, significant latent demand from the no trading alternative is alleviated through forecast-informed option contracts trading across all endowment scenarios. In many cases, for larger water rights endowments, HV demand for water can be fully satiated such that supply latency exists for LV farmers (LV farmer willingness to sell water exceeds HV farmer demand). The effect of supply latency on LV farmer FTU accumulation is negative at larger endowments, although forecast trust is comparable with other FTU accumulation and alternative action scenarios.

Comparing the two persistence (JP to IP; Fig. 6a to c) and no trading alternative scenarios (JN to IN; Fig. 6b to d), joint FTU accumulation is driven by HV farmers. This result is expected because of the comparative advantage they hold over LV farmers.

3.3. Robustness of forecast-informed water trade

While FTU accumulation over the observed hydrologic record provides insight with respect to generalized willingness to utilize forecasts, cooperative size and long-term stability may be affected by hydrologic conditions and contract period length. Here, the 85th, 50th and 15th percentile water rights investment outcomes from the 10,003 hydrologic simulations are evaluated to illustrate how forecast optimism and pessimism effect FTU accumulation and water rights investment by contract period across the range of water rights endowment scenarios (Fig. 7).

For the JP case, FTU accumulation and corresponding water rights investment decrease with increasing endowment (Fig. 7a). Rights investment during contract period $N = 1$ (Fig. 7a.; top) is generally higher than in $N = 2$ (Fig. 7a.; middle) and $N = 3$ (Fig. 7a.; bottom). This is precisely because FTU accumulation period $M = 1$ covers six years—one additional year over $M = 2$ and $M = 3$. This is true for all profit-based FTU accumulation and alternative action scenarios.

For all contract periods in the JP case, lower bound (15th percentile) and median outcomes are relatively consistent, although upper bounds (85th percentile) for $N = 2$ and $N = 3$ are reduced to the median outcome for half of the endowment scenarios (16,000–19,000 water rights). This result suggests that as water rights become available, it is increasingly likely that that only farmers with high risk tolerance will invest rights in the advanced forecast-informed water trading cooperative. However, the consistency between results for $N = 2$ and $N = 3$ suggest that a degree of rights investment stability is expected.

For the JN case (Fig. 7b) the number of rights invested by period increases over the range of endowment scenarios. Median rights investment outcomes for all contract periods and endowment scenarios includes all farmers with high risk tolerance and at least half of farmers from the medium risk tolerance group. For the five largest endowment scenarios (16,300–19,900 water rights), median outcomes suggest both the high and medium risk tolerant groups will invest water rights. For Contract Periods 2 and 3, the 85th percentile outcome suggests five FTUs may accumulate, such that all potential rights will be invested in the water-trading cooperative; corresponding FTU accumulation periods cover 5 years, thus only a portion of the low risk tolerant group may consider investment. Like the JP case, the JN case displays rights investment consistency in contract periods $N = 2$ and $N = 3$, which indicates the inter-cooperative arrangement reaches relative stability.

Under both individual profit-based FTU accumulation cases, IP (Fig. 7c) and IN (Fig. 7d), inter-endowment rights investments are less stable. Instability arises from independent FTU accumulation and rights investment decisions by HV and LV farmers. The effect supply and demand latency have on per-water right profits make the inter-cooperative arrangement unstable. In comparison to the JP and JN cases, IP and IN do not possess similar investment stability between contract periods $N = 2$ and $N = 3$, although the general pattern of both the median and upper and lower bounds for IP and IN are somewhat consistent during these periods.

Comparing across the four pairings, the joint cases (JP and JN) are best suited to provide inter-contract period and endowment stability, compared to the individual cases (IP and IN). However, rights investment response between JP and JN is drastically different; joint assessment of profitability by farmers is only preferred when otherwise no trading is possible (JN).

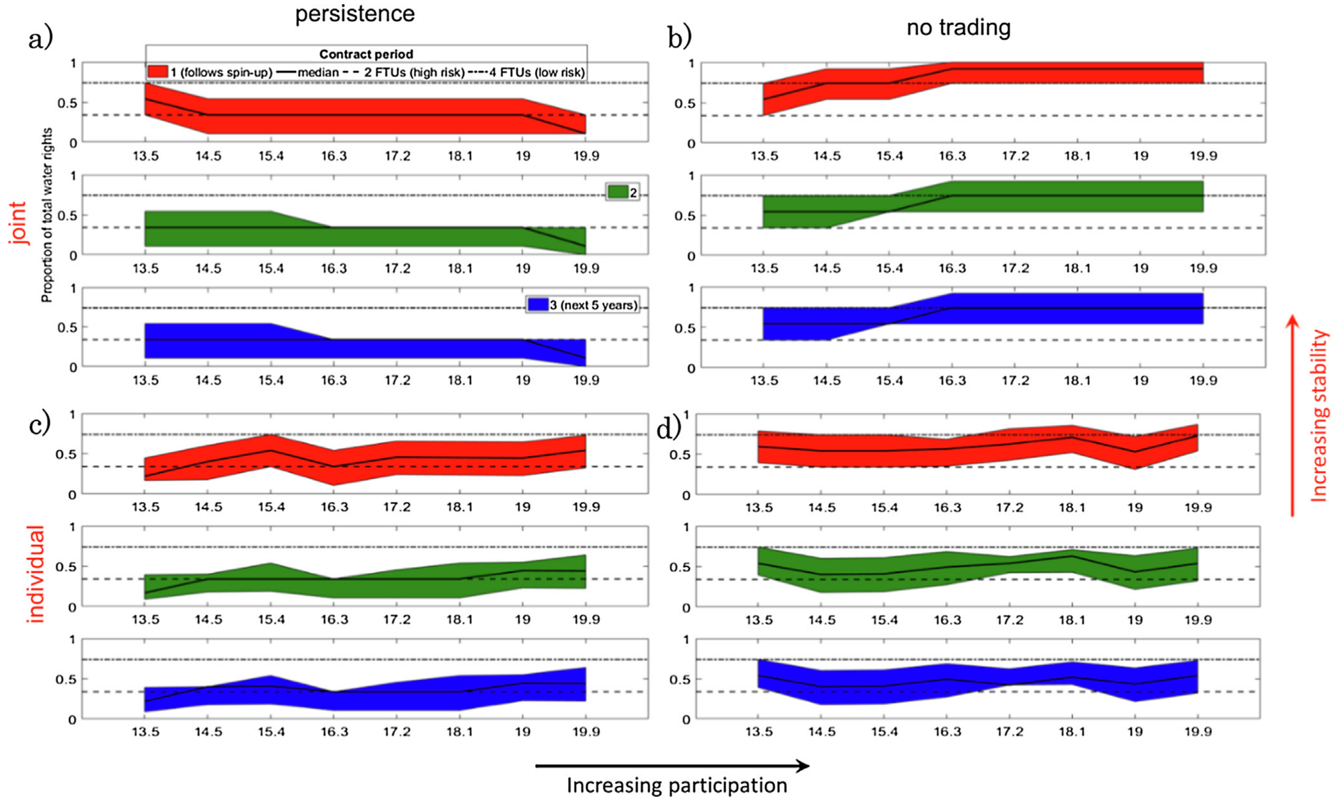

Fig. 7. Proportion of total water rights invested in forecast-informed trade versus inter-cooperative size (10,003 simulations, 2000–2015): a) JP, Contract Period 1 (top panel); Contract Period 2 (middle panel); Contract Period 3 (bottom panel), b) same as a) for JN, c) same as a) for IP, d) same as a) for IN. The horizontal lines represent FTU accumulation breakpoints for each risk group: the dashed line at 2 FTUs separates the high and medium risk groups, and the dashed and dotted line at 4 FTUs separates the medium and low risk groups.

This result is intriguing given that potential users of advanced forecast-informed OCs cannot control whether a competing persistence forecast-informed OC cooperative emerges. Clearly, advanced forecast users prefer JP, as investment of rights is maximized and stable between endowments—if there is no competition for water rights. If a competing cooperative emerges using persistence forecast information, rendering the no trading outcomes moot (Fig. 7b and d are infeasible), IP is the best option available for advanced forecast users. The preferred FTU accumulation basis is thus dependent upon the alternative action available to water rights users. Moving between profit-based FTU accumulation cases affects stability (inter-endowment stability in J greater than I), while moving between alternative actions affects participation (participation in N greater than P).

4. Discussion

Water rights endowment scenarios (cooperative size), hydrologic regimes (drought transpositions and random hydrologic simulations), trust unit accumulation bases, and alternative actions are all influential in evaluating forecast-based water rights investment strategies. These conditions are not unique to the Elqui Valley. The results suggest that forecast uptake, based on trust unit thresholds and risk group size, is evident. Expected investment of rights is variable (28% − 70% of total rights available) across the scenarios considered. The cooperative operates continuously and stably across contract periods, except for simulations containing a number (25% or more) of extreme drought years. In general, this suggests that forecast uptake is robust to most hydrologic regimes for farmers with high or medium risk tolerance preferences. This clearly highlights that while allocation forecast categorical skill (53%) is below what has been suggested as sufficient to evoke forecast acceptance and implementation by farmers (typically 60%–70%; (Bharwani et al., 2005; Ziervogel et al., 2005), by translating the forecast to specific end-user tailored actions through yield and economic models, it may possible to increase forecast appeal and uptake.

For this analysis, at least one forecast trust unit is necessary to prompt water rights investment by the most risk-tolerant farmer group. Given the adoption of five and six-year periods, forecast-informed decision making must be more skillful than an alternative in at least three of five (60%), or four of six (67%) years for positive trust units to accrue. Given the very high level of positive forecast trust unit accumulation, and appropriate water rights investments, forecast value has effectively increased through transformation.

An additional contribution of this work arises from simulating over varied water rights endowment scenarios. Varying rights ownership is synonymous with an analysis of how water scarcity may affect the size of the inter-cooperative arrangement. Increasing the pool of rights increases the net allocation received, given the total number of irrigated hectares remains constant. As such, the results presented here reveal inter-cooperative water-trading sensitivity to changes in water scarcity. Only when high and low value farmers choose to jointly determine forecast trust unit accumulation and face a persistence forecast-informed water-trading alternative do increased endowments (decreased water scarcity) negatively impact realized water rights investment. This is not the case for the other three scenarios addressed. This suggests that forecast value to users increases with, or is not sensitive to, expanding endowments. That is, forecast value is robust to several water scarcity scenarios.

The four scenarios proposed serve to highlight likely conditions under which water-trading cooperatives may form. Alternative actions available to farmers have some effect on rights investment (the no trading alternative results in generally more cooperative rights investment than the persistence alternative) but are not controllable by those interested in formation of trading cooperatives. For example, if forecast-informed water trading cooperatives form, the members cannot control whether a competing persistence forecast-based trading cooperative emerges. As such, interested farmers must consider which forecast trust unit accumulation method to "advertise" to potential participants—joint or individual expected profitability.

The profit-based trust unit accumulation methodology influences long-term rights investment stability across endowment scenarios. This is made clear comparing joint (Fig. 7a & b) to individual profit-based trust accumulation (Fig. 7c & d). While joint profit-based accumulation has a substantial upside in terms of potential rights investment (Fig. 7b), if a competing persistence cooperative forms (Fig. 7a.) rights investment expectations fall. For the joint cases, differences in expected investment increase with larger endowment scenarios. For this reason, if investment stability is preferred, farmers may be inclined to advertise individual profit-based accumulation statistics (Fig. 7c & d), which are less sensitive to alternative actions over the range of endowments. This is reinforced by the likelihood of larger endowment scenarios being the most realistic of those simulated (> 18,000 water rights; (Zunino et al., 2009).

This work treats farmers in the Elqui as approximated by risk groups with underlying attitudes toward forecast trust. However, the true nature of risk attitudes is unknown. The group-based approach used here mimics that of similar studies but is flexible such that alterations to the number and size of risk-groups, forecast trust thresholds, and characterization of intra-group farmer distributions may be altered. Ground-truthing risk attitudes through focused interactions with farmers of varied crop-types in the Elqui should be conducted to confirm the risk attitude model.

Another limitation of the research presented here is that rights must either be invested in the advanced forecast-informed water trading cooperative or in only one alternative action. For example, if insufficient forecast trust units are accumulated during a specified period, and the alternative action analyzed is a persistence-informed water trading cooperative, rights holders must "choose" one of these options. The model does not permit the option to pursue a no trading alternative. It follows that if no trading is the available alternative action, the persistence alternative is not available. Thus, the results here limit the total number of alternatives simulated.

5. Conclusions

This work postulates that to provide a fair assessment of the option value of forecasts, here translated to inform water option contracts available to water rights holders engaged in irrigated agriculture, the robustness of the forecasts to both varied hydrologic conditions and risk attitudes among rights holders must be tested. Here a robustness framework is presented to evaluate water rights investment by farmers across many water rights endowment scenarios when presented with alternative water trading engagement strategies. Results indicate that water-trading cooperatives will form and operate continuously to promote water market-scale economic benefits and use efficiency, based on the emergence of forecast-informed option contracts used to facilitate temporary water transfers.

Specifically, findings here suggest that forecast uptake is not only expected but also robust to hydrologic variability and simulations of water scarcity. While rights invested between users is expected to fluctuate in response to prolonged droughts, probabilistic simulations suggest that given a 25% or less chance of extreme drought in any year, investment of rights reaches stability across a range of likely water rights ownership scenarios.

This framework is likely transferable beyond the Elqui Valley case study. Wherever water rights are implemented and may be traded by those who seek to use water as an input to production, user demand may be derived, and transparent water-trading rulesets may be implemented. Yet even in cases where the framework may not be directly applied (i.e. rights are not tradeable, infrastructure does not permit efficient movement of water), the results presented here illustrate the appeal of even marginally skillful season-ahead hydrologic forecasts enhanced through translation. The full value of climate and hydrology forecast information may not be realized unless it is tailored specifically to end users.

The conclusions of this study serve to support the inclusion of season-ahead hydrologic forecasts as a critical component of water systems management. The connectedness of the natural and human components of water systems warrants forecast development and integration consistent with sectoral goals and user preferences to catalyze efficient water systems.

CRediT authorship contribution statement

Justin D. Delorit: Visualization. **Paul J. Block:**Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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There are no real or perceived financial conflicts of interests for any author.

There are no other affiliations for any author that may be perceived as having a conflict of interest with respect to the results of this paper.

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