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# The Illiquidity of Water Markets: Efficient Institutions for Water Allocation in Southeastern Spain\*

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## Abstract

Water is an essential good for human life but there is controversy on whether it should be allocated using markets. In 1966, the irrigation community in Mula (Murcia, Spain) switched from a market institution, an auction which had been in place in the town for over 700 years, to a system of fixed quotas with a ban on trading to allocate water from the town's river. We present a model in which farmers face liquidity constraints (LC) to explain why the new, non-market institution is more efficient. We show that farmers underestimate water demand in the presence of LC. We use a dynamic demand model and data from the auction period to estimate both farmers' demand for water and their financial constraints, thus obtaining unbiased estimates. In our model, markets achieve the first-best allocation only in the absence of LC. In contrast, quotas achieve the first-best allocation only if farmers are homogeneous in productivity. We compute welfare under both types of institutions using the estimated parameters. We find that the quota is more efficient than the market. This result implies that one should be cautious in advocating for water markets, especially in developing areas where LC might be a concern.

**JEL CODES:** D02, D53, G14, Q25

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# 1 Introduction

Water allocation is a central concern of policy discussions around the world. Seventy percent of fresh water usage worldwide is for irrigation. Water scarcity is extremely acute in places such as India, Latin America, and the U.S. (Vörösmarty *et al.*, 2010). Water markets (*e.g.* water auctions) are emerging as the preferred institution to allocate water in the developed world, particularly in dry regions of the U.S. and Australia (Grafton *et al.*, 2011). In the absence of *frictions*, a water auction is efficient because it allocates water according to the valuation of the bidders. When frictions are present, however, markets may not be efficient. Consider, for example, the friction that arises when bidders may not have enough cash to pay for water won in an auction (*i.e.* some bidders may be liquidity constrained). An auction allocates water to the highest bidders who are not liquidity constrained. A market failure occurs if some bidders, who are liquidity constrained, have higher valuations than the bidders who are not liquidity constrained. In such a case, other mechanisms may allocate water more efficiently than auctions.

When water markets are used, they are usually regulated (rather than a free market). In regulated water markets, a common measure of efficiency is to infer gains from trade from price differences. Such a measure is difficult due to barriers across districts and different regulatory frameworks. Recovering demand in such cases requires strong assumptions about market participants (Libecap, 2011).

In this paper, we analyze how a market institution (an auction system) performs relative to a non-market institution (a quota system as described below) as a water allocation mechanism in the presence of frictions. The data in this paper comes from water auctions in a self-governed community of farmers in Mula, Spain. This allows us to exploit a unique scenario where a free market institution operated under a stable regulatory framework for over 700 years. From around 1244 until 1966, citizens of Mula used auctions to allocate water from their river among farmers. The farmers used this water for agricultural purposes. In 1966, the auction system was replaced by a quota system. Under the quota system, farmers

who owned a plot of fertile land were entitled to a fixed amount of water—proportional to the size of their plot—for irrigation.

Frictions arose in Mula when farmers did not have enough cash in the summer to purchase water from the auction. We provide evidence of these liquidity constraints (LC) in Section 2.4. Under the auction system, the price of water increased substantially in summer because (i) the agricultural products cultivated in the region (apricots, peaches, oranges, *etc.*) needed more water during this season when fruit grows more rapidly, increasing demand for water in the auction; and (ii) weather seasonalities in southern Spain generated less rainfall in summer than in winter. These conditions made summer the “critical” season.

In the lead article of the first volume of the *American Economic Review*, Coman (1911) pointed out this issue: “In southern Spain, where this system obtains and water is sold at auction, the water rates mount in a dry season to an all but prohibitive point.” This means that during the critical season, only “wealthy” farmers could afford to buy water. But “poor” farmers with the same production technology (*i.e.* the same agricultural products) would also benefit from buying water during the critical season. Indeed, we find that poor farmers bought less water during the critical season than wealthy farmers who had the same type of agricultural products and the same number of trees. A natural question arises: How did the institutional change from auctions to quotas affect welfare in the presence of LC?

There is no consensus among historians about how this institutional change impacted water allocation efficiency. Some contemporaneous observers argued that auctions were efficient. The following quotation is from historian Musso y Fontes: “When the farmer irrigates for free, he demands a lot of water. When he is paying for the water, he demands as little as possible. With the auction, the allocation [of water] occurs at the proper level” (cited by Muñoz, 2001). However, Musso y Fontes himself owned water property rights. Observers without water property rights argued that auctions allocated water inefficiently during the critical season. One of these observers was the director of the National Engineering School, Juan Subercase: “[The Waterlords sell the water] piece by piece, during the critical season

when the crops are at risk, speculating [...] over the desperate and distressed farmer, who is willing to make the highest sacrifice in order to get a drop of water” (cited by Muñoz, 2001).<sup>1</sup> Indeed, most of the other towns in the region employed the quota system for centuries (*e.g.* Murcia, Caravaca, Jumilla, *etc.*). Mula’s auction system was the exception, not the rule. Subercase’s argument also helps to explain why the farmers of Mula were happy to switch from the auction system to the quota system (González Castaño and Llamas Ruiz, 1991).

In this paper, we empirically investigate how this institutional change—from auctions to quotas—affected efficiency as a measure of welfare. We propose an econometric model in which water for irrigation has diminishing returns and farmers are heterogeneous in two dimensions: their willingness to pay (productivity) and their ability to pay for the water (cash holdings). In the absence of LC, an auction system achieves the first-best (FB) allocation. On the other hand, in the absence of heterogeneity in the farmers’ productivity, a fixed quota system achieves the FB allocation.<sup>2</sup> In our empirical setting farmers are heterogeneous in their productivity and some farmers are liquidity constrained. In this general case, the efficiency of auctions relative to quotas is ambiguous. It is then an empirical question to assess which of these institutions is more efficient. To the best of our knowledge, there has been no empirical study that investigates the efficiency of auctions relative to quotas in the presence of liquidity constrained bidders.

We start our empirical analysis by estimating the demand for water under the auction system. To estimate demand, it is necessary to account for three features of the empirical setting. First, irrigation increases the moisture level of the land, thus reducing future demand for water. It creates an intertemporal substitution effect where water today is an imperfect substitute for water tomorrow because it evaporates over time. This introduces dynamics into the irrigation demand system, similar to those of demand for storable goods. The soil

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<sup>1</sup>Both translations from the original in Spanish are ours.

<sup>2</sup>If capital markets are perfect or if all farmers are sufficiently wealthy, then the auction system achieves the FB allocation. If there is no heterogeneity (*i.e.* if all farmers have the exact same production function), then the quota system achieves the FB allocation. If there is no heterogeneity and all farmers are sufficiently wealthy, then both mechanisms (auctions and quotas) achieve the FB allocation.

moisture level plays an analogous role to that of inventory in storable goods demand systems (*e.g.* Hendel and Nevo, 2006). Second, some farmers are liquidity constrained. Wealthy farmers strategically delay their purchases and buy water during the critical season, when agricultural products need water the most. Poor farmers, who may be liquidity constrained, buy water before the critical season in anticipation of price increases. Finally, weather seasonality increases water demand during the critical season, when fruit grows more rapidly. Seasonality shifts the whole demand system, conditional on intertemporal substitution and LC.

To account for the intertemporal substitution effect, we condition on the moisture level of the soil, a key determinant of water demand. The moisture level is not directly observable (similar to Hendel and Nevo, 2006, where the inventory is not directly observed). However, we observe rainfall and irrigation. We apply findings from the agricultural engineering literature to construct a moisture variable for each farmer. The moisture variable measures the amount of water accumulated in each farmer's plot.

We show that ignoring the presence of LC biases the estimated (inverse) demand and demand elasticity downwards. To see this, consider the decrease in demand due to an increase in price during the critical season. When farmers are liquidity constrained, the decrease in demand has two components: (1) the decrease in demand due to the price being greater than the valuation of certain farmers; and (2) the decrease in demand due to some farmers being liquidity constrained, even when their valuation is above the prevailing price. If we do not account for the second component, we would attribute this decrease in demand to greater price sensitivity. Thus, one would incorrectly interpret LC as more elastic demand, biasing the estimated demand downwards.

To identify LC, we use the fact that wealthy farmers are never liquidity constrained, while poor farmers *may* be liquidity constrained. We focus on the set of farmers who only grow apricot trees and who thus share the same production function. Water, in our setting, is an intermediate good used to produce apricots. Thus, the demand for water is independent of



the income (or wealth) of the farmer as long as the farmer has enough cash to pay for the water (*i.e.* no income effects).

In our econometric model, the farmer's utility has three components. First, the apricot production function that transforms water into apricots. This production function is obtained from the agricultural engineering literature. Second, the cost of producing the apricots, measured as the amount spent on water plus an irrigation cost. Finally, an idiosyncratic productivity shock that is farmer specific. Conditional on the soil moisture level, the type of agricultural product (*i.e.* apricot), and the number of trees, farmers' productivity is assumed to be homogeneous up to the idiosyncratic shock. This gives us the exclusion restriction to identify the other source of heterogeneity, LC.

As mentioned above, estimating demand using data for all farmers results in an underestimation of the price elasticity of demand. But wealthy farmers are never liquidity constrained. So we estimate demand using only data on wealthy farmers. For the estimation, we construct a conditional choice probability estimator (Hotz and Miller, 1993). We then use the estimated demand system and data on poor farmers to estimate the probability for poor farmers of being liquidity constrained each week. We rely on the variation of two sources of financial heterogeneity, urban real estate value and revenue from previous years' harvests, in order to identify these parameters.

We use the estimated demand system to compare welfare under auctions, quotas, and the first-best allocation. We consider the following allocation mechanisms: (1) Auctions,  $Ac$ , wherein water units are assigned to the farmer who bought them as observed in the data; (2) Quotas with sequential assignment,  $QX\%$ , wherein every time we observe that a farmer bought a unit of water, the complete unit of water is assigned among the  $X\%$  of farmers who went without irrigation the longest, proportional to their amount of land; and (3) the first-best allocation,  $FB$ , wherein every time we observe that a farmer bought a unit of water, the complete unit of water is assigned to the farmer who values water the most.

We show that the following ranking holds in terms of efficiency:  $FB > Q25\% > Ac$ . In

$Q25\%$ , complete units of water are allocated among the 25% of farmers who have received less water in the past, in proportion to amount of land. The welfare under  $Q25\%$  is greater than under  $Ac$ . Quotas increase efficiency when units are allocated according to  $Q25\%$ , which is a result of the concavity of the production function, the presence of LC, and the absence of heterogeneity in farmers' productivity (all farmers have the same production function: the apricot production function). Under  $Q25\%$  there are still gains to be made relative to the  $FB$  allocation, suggesting that there is some heterogeneity in productivity. In Mula, the quota allocation mechanism was close to  $Q25\%$  because every farmer was assigned a certain amount of water every three weeks, proportional to their plot's size (González Castaño and Llamas Ruiz (1991)).<sup>3</sup>

In summary, we make three main contributions: (1) we combine a novel data set, including detailed financial and individual characteristic information, with a new econometric model to estimate demand in the presence of storability, LC, and seasonality; (2) we investigate the efficiency of auctions relative to quotas in the presence of liquidity constrained bidders by exploring a particular historical institutional change in southern Spain (Mula); (3) from an historical perspective, we conclude that the Mula institutional change was welfare improving because the quota system more often allocated water units following farmers' valuations than did the auction system.

## 1.1 Literature Review

Scholars studying the efficiency of irrigation communities in Spain have proposed two competing hypotheses to explain the coexistence of auctions and quotas. On the one hand, Glick (1967) and Anderson and Mass (1978) claimed that auctions are more efficient than quotas, absent operational costs. They argued that both systems are nevertheless observed because the less efficient system (quotas) is simpler and easier to maintain. Hence, once operational

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<sup>3</sup>In  $Q50\%$ , complete units of water are allocated among the 50% of farmers who have received less water in the past, in proportion to their amount of land. The welfare under  $Q50\%$  is similar to the welfare under  $Ac$ . In  $Q100\%$ , complete units of water are allocated uniformly at random among all farmers, in proportion to amount of land. The welfare under  $Q100\%$  is lower than under  $Ac$ . See Section 6 for details.

costs are taken into account, quotas are more efficient than auctions in places with less water scarcity. This hypothesis is supported by observations of auctions in places where water is extremely scarce (Musso y Fontes, 1847; Pérez Picazo and Lemeunier, 1985). On the other hand, many contemporaneous and current historians who study the traditional organizations of the Spanish *Huertas* (irrigated orchards) took a different approach.<sup>4</sup> They argued that the owners of the water rights had political power and were concerned only with their revenues, regardless of the overall efficiency of the system.

Along the same lines, Garrido (2011) has claimed that auctions were used in places where the local elite was powerful. Therefore, we would expect a quota system only if the local elite is not powerful (Acemoglu and Robinson, 2008). As Rodríguez Llopis (1998) pointed out, the institutional configuration in place in each town by the end of the Middle Ages was the outcome of tensions between the Crown, the Castilian aristocracy, the regional nobility, and the local elites in existence since the 13<sup>th</sup> century. Nonetheless, none of these scholars considered whether auctions might be less efficient than quotas. (See Espín-Sánchez, 2015, for a discussion of the institutional change.)

The effect that imperfect capital markets have in the real economy has also been studied in the development literature. Udry (1994) studied how state-contingent loans are used in rural Nigeria to partially insure a bad harvest. Jayachandran (2013) showed how the presence of LC among land owners in Uganda can make an upfront payment in cash much more effective than the promise of future payments.

We are not aware of any empirical paper analyzing the effect of LC in an auction setting. Pires and Salvo (2015) found that low income households buy smaller sized storable products (detergent, toilet paper, *etc.*) than high income households, even though smaller sized products are more expensive per pound. They attribute this puzzling result to low income households being liquidity constrained.

We estimate a dynamic demand model with seasonality and storability. There is a vast

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<sup>4</sup>Contemporaneous historians include Aymard (1864), Díaz Cassou (1889) and Brunhes (1902). Current historians include González Castaño and Llamas Ruiz (1991).

literature in empirical industrial organization studying dynamic demand (*e. g.* Boizot *et al.*, 2001; Pesendorfer, 2002; Hendel and Nevo, 2006, 2011; Gowrisankaran and Rysman, 2012).<sup>5</sup> None of these papers address how LC affect demand. To the best of our knowledge, ours is the first paper that proposes and estimates a demand model with storability, seasonality and LC. Timmins (2002) studies dynamic demand for water and is closest to our paper. He estimates demand for urban consumption rather than demand for irrigation. He uses parameters from the engineering literature to estimate the supply of water. We use parameters from the agricultural engineering literature to determine the demand structure, as well as soil moisture levels (see appendix A.2).

## 2 Historical background and Data

### 2.1 History and Origins<sup>6</sup>

During the reign of Ibn Hud (1228-1238), the Kingdom of Murcia enjoyed some prosperity and stability. When Ibn Hud was murdered in 1238, the kingdom was dismembered. This same year Jaime I (King of Aragon) conquered Valencia and prepared to march south. Castile was also advancing to the south, expanding its territory at the expense of the now fragile Kingdom of Murcia. By 1242, Castile had conquered most of the Kingdom. Ahmed, the son of Ibn Hud, traveled to Alcaraz (Toledo) to meet prince Alfonso. They agreed that what remained of the Kingdom of Murcia would become a protectorate of Castile.

The cities of Mula and Lorca rejected this agreement. In April 1244, Alfonso was in Murcia with his army ready to attack Mula (the closest of the rebel cities). After Mula was conquered, the army moved to Lorca, which surrendered by the end of June. The government of Mula and Lorca was given to the Order of Santiago, while the government of the city of Murcia was given, in part, to the descendants of Ibn Hud according to the terms of the

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<sup>5</sup>See Aguirregabiria and Nevo (2013) for a recent survey.

<sup>6</sup>This section is based on Rodriguez Llopis (1998).

Alcaraz Treaty. However, the Order of Santiago and the Order of the Temple had absolute authority over the cities of Mula and Lorca respectively, since the cities were conquered by force. As with much of the Spanish *Reconquista*, Christian populations were brought to the area with the goal of establishing a Christian base. Hence, the new Christian settlers in Mula started *tabula rasa* and created new institutions (see Espín-Sánchez, 2015).<sup>7</sup>

Under these new institutions, the owners of the water property rights (Waterlords) were different persons than the land owners (farmers). The Waterlords established a well-functioning cartel (*Heredamiento de Aguas*) which lasted through the pre-modern era, despite the many political changes that occurred in Spain. The land owners were small proprietors, with family-size plots, who soon after created their own association, *Sindicato de Regantes*.

## 2.2 Environment

Southeastern Spain is the most arid region of Europe. It is located to the east of a mountain chain, the Prebaetic System. Most years are dryer than the average. There are only a few days of torrential rain but they are of high intensity. For example, 681 millimeters (*mm*) of water fell in Mula on one day, 10<sup>th</sup> October 1943, while the yearly average in Mula is 326 *mm*. Summers are dry and rain falls mostly during fall and spring. Insolation is the highest in Europe. Rivers flowing down the Prebaetic System provide the region with the water needed for irrigation.

Weekly prices for water in the auctions are volatile. They depend on the season of the year and the amount of rainfall. But rainfall is hard to predict, making difficult to predict the need for cash to buy water in the auction. Water demand is seasonal, peaking during the weeks before the harvest when fruit grows most rapidly. Farmers sell their output after the harvest (once per year). Only then the farmers collect the cash (revenue) from growing their agricultural products. Hence, the weeks when farmers need cash the most to pay for water in the auctions (the weeks before the harvest) are the weeks farthest away from the

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<sup>7</sup>Notice that this initial shock in institutions is similar to that in Chaney (2008).

last harvest (the last time they collected the revenue). As a consequence, poor farmers who do not have other sources of revenue may be liquidity constrained.

Given that demand is seasonal, farmers take into account the joint dynamics of their demand for water and of the prices of water in the auction when making purchasing decisions. Water today is an imperfect substitute for water tomorrow. Future prices of water are difficult to predict. Farmers consider current prices of water and form expectations about future prices of water. A farmer who expects to be liquidity constrained during the critical season—when the demand is highest—may decide to buy water several weeks before the critical season, when the price of water is lower. We allow for farmers to save so that after a rainy year with low water prices, they are less likely to be liquidity constrained.

A farmer who expects to be liquidity constrained in the future will try to borrow money. However, poor farmers in Mula did not have access to credit markets.<sup>8</sup> However, even if a credit market is in place, loans may not be granted. In the presence of limited liability (*i.e.* the farmer is poor) and non-enforceable contracts (*i.e.* poor institutions), endogenous borrowing constraints emerge (see Albuquerque and Hopenhayn, 2004, for a model of endogenous liquidity constraints). Hence, even if a credit market exists, non-enforceable contracts would prevent the farmer from having cash when they need it most.<sup>9</sup>

## 2.3 Institutions

In this subsection, we describe two institutions that allocated water from the river to farmers in most cities of southeastern Spain.

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<sup>8</sup>Personal interviews with surviving farmers confirm that some farmers were liquidity constrained—they did not have enough cash to buy their desired amount of water—yet they did not borrow money from others.

<sup>9</sup>In contrast to German credit cooperatives (Guinnane, 2001), the farmers in southeastern Spain were not able to create an efficient credit market. Spanish farmers were poorer than German farmers and, more importantly, the weather shocks were aggregate (not idiosyncratic) and greater in magnitude. Hence, in order to reduce the risk, Spanish farmers should resort to external financing. However, external financing has problems such as monitoring costs and information acquisition that credit cooperatives do not have.

**Auctions.** Since the 13<sup>th</sup> century, the mechanism to allocate water among farmers was a sequential outcry ascending price (or English) auction. The basic structure of this sequential English auction in use in Spain remained unchanged from the 13<sup>th</sup> century until 1966, when the last auction was run. The auctioneer sold by auction each of the units sequentially and independently of each other. The auctioneer tracked the name of the buyer of every unit and the price paid by the winner. Farmers had to pay in cash on the day of the auction.<sup>10</sup>

Water was sold by *cuarta* (quarter), a unit that denoted the right to use water flowing through the main channel during three hours at a specific date and time. Property rights to water and land were independent: some individuals, not necessarily farmers, were Waterlords. That is, Waterlords owned the right to use the water flowing through the channel. The other farmers who participated in the auctions owned land.

Water was stored at the main dam (*Embalse de La Cierva*).<sup>11</sup> A system of channels delivered water to the farmer's plot. Water flowed from the dam through the channels at approximately 40 liters per second. Each unit of water sold at auction (*i.e.* the right to use water from the canal for three hours) carried approximately 432,000 liters of water. During our sample period, auctions were held once a week, every Friday.

During each session, forty units were auctioned: four units for irrigation during the day (from 7:00 AM to 7:00 PM) and four units for irrigation during the night (from 7:00 PM to 7:00 AM) on each weekday (Monday to Friday). The auctioneer first sold twenty units corresponding to the night-time and then twenty units corresponding to the day-time. Within the day and night groups, units were sold starting with Monday's four units and finishing with Friday's units. Our sample consists of all water auctions in Mula from January 1955 until July 1966, when the last auction was run.

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<sup>10</sup>Allowing the farmer to pay after the critical season would help mitigate the problems created by the LC and would increase the revenue obtained in the auction. The fact that the payment should be made in cash, as explicitly written in their bylaws, suggests that the water owners were concerned about repayment after the critical season (*i.e.* non enforceable contracts).

<sup>11</sup>This dam was built in 1929. Before this dam was built, water was stored at the smaller dam *Azud del Gallardo*.

**Quotas.** On August 1, 1966 the allocation system was changed from an auction to a two-sided bargaining system. In the bargaining system, the *Heredamiento de Aguas* and the *Sindicato de Regantes* fixed a water price, to be renegotiated every six months. Since 1966, the *Sindicato de Regantes* has allocated water to each farmer through a fixed quota.

Under this system, water ownership was tied to land ownership. Every plot of land was assigned some amount of irrigation time during each three week round (quota). The amount of time allocated to each farmer was proportional to the size of their plot. Every December, a lottery assigned a farmer's order of irrigation within each round. The order did not change during the entire year. At the end of the year, farmers paid a fee to the *Sindicato* proportional to the size of their plot. Farmers payed after the critical season and were not liquidity constrained.<sup>12</sup> These fees covered the year's operational costs: guard salaries, channel cleaning, dam maintenance, *etc.*<sup>13</sup>

## 2.4 Data

We examine a unique panel data set where each period represents one week and each individual represents one farmer. Thus, the unit of observation is a farmer-week. The data was collected from four different sources. The first source is the weekly auction. For the period from January 1955 until the last auction in July 1966 we observe the price paid, the number of units bought, the date of the purchase, and the date of the irrigation. This data was obtained from the municipal archive of Mula.<sup>14</sup> The second source is rainfall measurements.<sup>15</sup> The third source is a cross sectional agricultural census from 1955. The census data contains information regarding the farmer's plots, including type of agricultural product, number of

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<sup>12</sup>The farmer was the owner of the water under the quota system, so the price that the farmer paid was the average cost of operation, which was smaller than the average price paid per unit of water under the auction system. A full accounting of costs will include the amortization of the value of water rights.

<sup>13</sup>During the first years of the quota system, the fee also included the payments made to the *Heredamiento de Aguas* to buy the water rights.

<sup>14</sup>From the section *Heredamiento de Aguas*, boxes No.: HA 167, HA 168, HA 169 and HA 170.

<sup>15</sup>We obtain the rainfall information from the *Agencia Estatal de Meteorología*, AEMET (the Spanish National Meteorological Agency).



trees, production quantity, and sale price.<sup>16</sup> The final source is real estate tax records from 1955. We later use this information to identify liquidity constraints.

Table 1 shows the summary statistics of selected variables used in the empirical analysis. Detailed information about the data can be found in appendix A.1.

Table 1: Summary Statistics of Selected Variables.

| Variable                                    | Mean    | St. Dev. | Min   | Med   | Max    | No. obs. |
|---|---------|----------|-------|-------|--------|----------|
| Weekly rain ( <i>mm</i> )                   | 8.29    | 37.08    | 0     | 0     | 423.00 | 602      |
| Water price ( <i>pesetas</i> ) <sup>a</sup> | 326.157 | 328.45   | 0.005 | 217.9 | 2,007  | 602      |
| Real estate tax ( <i>pesetas</i> )          | 482.10  | 1,053.6  | 0     | 48    | 8,715  | 496      |
| Area ( <i>ha</i> )                          | 2.52    | 5.89     | 0.024 | 1.22  | 100.1  | 496      |
| Number of trees <sup>b</sup>                | 311.3   | 726.72   | 3     | 150   | 12,360 | 496      |
| Units bought                                | 0.0295  | 0.3020   | 0     | 0     | 4      | 145,684  |

Notes: This is the sample of all farmers. We found 496 census cards in the archive. We were able to fully match 242 individuals to the auction data. The agricultural census include farmers who have only *secano*, or dry, lands and thus, are not in our sample. The sample after the matching process consists of 602 weeks and 242 individuals for a total of 145,684 observations.

<sup>a</sup> Water price is the weekly average price in the auction.

<sup>b</sup> Number of trees includes vines.

Source: Own elaboration.

**Auction Data.** Auction data (602 weeks) can be divided into three categories based on bidding behavior and water availability: (i) Normal periods (300), where for each transaction the name of the winner, price paid, date and time of the irrigation for each auction were registered; (ii) No-supply periods (295), where due to water shortage in the river or damage to the dam or channel—usually because of intense rain—no auction was carried out, and finally; (iii) No-demand periods (7), where not all 40 units were sold due to lack of demand (the price dropped to zero due to recent rain). In the main estimation we use data for the period 1955-66.

**Rainfall Data.** In the Mediterranean climate, rainfall occurs mainly during spring and fall. Peak water requirements for products cultivated in the region are reached in spring

<sup>16</sup>Detailed census data is obtained from the section *Heredamiento de Aguas* in the historical archive of Mula, box No. 1,210.

and summer, between April and August. The coefficient of variation of rainfall is 450% ( $37.08/8.29 \times 100$ ), indicating that rainfall varies substantially.

**Agricultural Census Data.** The Spanish government conducted an agricultural census in 1955 to enumerate all cultivated soil, production crops, and agricultural assets available in the country. The census recorded the following individual characteristics about farmers' land: type of land and location, area, number of trees, production, and the price at which this production was sold in the census year. We match the name of the farmer on each census card with the name of the winner of each auction.

**Urban Real Estate Tax Data.** In order to credibly identify the source of financial constraints we require a variable related to farmers' wealth, but unrelated to their demand for water. We use urban real estate taxes. (Note that farmers grow their agricultural products in rural areas.) The idea is that farmers with expensive urban real estate are wealthier than farmers who own inexpensive urban real estate. Thus, farmers with expensive urban real estate are unlikely to be liquidity constrained. On the other hand, the value of urban real estate owned should not affect the farmer's production function (*i.e.* the farmer's willingness to pay), conditional on the type of agricultural product, the size of the plot, and the number of trees. Hence, after accounting for these variables the value of the urban real estate should not be correlated with the farmer's demand for water, which is determined by the production function of the agricultural product (the apricot production function in our case). We later use this exclusion restriction to identify liquidity constrained farmers.

## 2.5 Preliminary Analysis

In this subsection, we provide descriptive patterns from the data. There are four main fruit trees grown in the area: orange, lemon, peach and apricots. Oranges are harvested in winter and prices are low during their critical season, thus farmers are unlikely to face liquidity

constraints (LC). The other three types of trees are harvested in the summer. Among them, apricots are the most common crop, thus our focus there.

In Table 2, we restrict attention to farmers who grow only apricot trees. The table displays OLS regressions. We regress the number of units bought by each farmer in a given week on several covariates. The variable “High urban real estate” is a variable that equals one if the value of the urban real estate owned by the farmer is greater than the sample median, and 0 otherwise. The idea behind this dummy variable is that farmers who are wealthy enough are never liquidity constrained. They do not have to pay rent for their houses and they even can collect rent from their urban real estate to obtain cash during the critical season, financing their purchases. Consider two farmers who are growing apricots, who have the same number of trees, and who are not liquidity constrained. Water demand is determined by the water need of the tree according to the apricot production function. These two farmers should have the same demand for water up to an idiosyncratic shock. Therefore, there is no relationship between the demand for water and the monetary value of urban real estate.<sup>17</sup> Columns 1 and 2 shows that “poor” farmers buy less water overall.

In columns 3 and 4 we include an interaction between “High urban real estate” and “Critical season.” The variable “Critical season” is a dummy variable that equals 1 if the observation belongs to a week during the critical season and 0 otherwise.<sup>18</sup> During the critical season the auction price of water increases substantially because farmers need water the most. In the case of apricots the critical season also coincides with the beginning of summer, when the prices are highest. The interaction term is positive and statistically different from zero. This means that wealthy farmers buy substantially more water than poor farmers during the critical season. Poor farmers who are liquidity constrained are not able to buy water during the weeks in which they need it the most. Columns 3 and 4 show that the effect of LC on the demand for water is concentrated on the critical season.

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<sup>17</sup>We obtain similar results using the 40<sup>th</sup> or the 60<sup>th</sup> percentiles of the distribution of urban real estate. Results are available upon request.

<sup>18</sup>See appendix A.2 for a discussion on how the critical season is defined.

Table 2: Demand for Water and Urban Real Estate.

| Number of units bought                       | (1)                   | (2)                   | (3)                   | (4)                   |
|--|-----------------------|-----------------------|-----------------------|-----------------------|
| High urban real estate                       | 0.0255***<br>(0.0063) | 0.0235***<br>(0.0062) | 0.0133**<br>(0.0066)  | 0.0126*<br>(0.0066)   |
| (High urban real estate) x (Critical season) |                       |                       | 0.0702***<br>(0.0117) | 0.0602***<br>(0.0122) |
| Covariates                                   | No                    | Yes                   | No                    | Yes                   |
| Number of observations                       | 14,448                | 14,448                | 14,448                | 14,448                |

Notes: All regressions are OLS specifications. The sample is restricted to farmers who only grow apricots. The dependent variable is the number of units bought by each individual farmer during a given week. “High urban real estate” is a dummy variable that equals 1 if the value of urban real estate of the farmer is above the median. “Critical season” is a dummy that equals one if the observation belongs to a week during the critical season. “Covariates” are the price paid by farmers in the auction, the amount of rainfall during the week of the irrigation, the farmer’s soil moisture level, and the farmer’s number of trees. Standard errors in parentheses. \*  $p < 0.10$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ .

Table 3: Relationship between Size and Composition of Plots and Wealth.

|                        | (1)                  | (2)                     | (3)                    | (4)                           | (5)  |
|------------------------|----------------------|-------------------------|------------------------|-------------------------------|--|
|                        | Area Total<br>(Ha)   | Area with<br>trees (Ha) | Fraction<br>with trees | Revenue<br>( <i>pesetas</i> ) | Revenue/<br>area<br>( <i>pesetas/m<sup>2</sup></i> ) |
| Urban real estate      | 34,023***<br>(9,747) | 22,069***<br>(7,031)    | -0.0355<br>(0.0320)    | 23,894***<br>(4,024)          | -0.1797<br>(0.7543)                                  |
| Number of observations | 388                  | 388                     | 388                    | 388                           | 388  |

Notes: All regressions are OLS specifications. The sample is restricted to farmers who only grow apricots. The dependent variable is the variable in each column. “Urban real estate” measures the value of a farmer’s urban real estate in *pesetas*. Standard errors in parentheses. \*  $p < 0.10$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ .

Table 3 shows that wealthy farmers have bigger plots. One concern that arises in Table 2 is that the effect may be due to differences in the size of the plots. Since farmers can only buy whole units, there may be economies of scale in water purchases which only wealthy farmers, who own bigger plots, can take advantage of. Table 4 displays similar estimates to those in Table 2 but normalized for the number of trees on each farmer’s plot. Columns 3 and 4 show that a farmer’s wealth has no effect on their demand for water outside the critical season. However, the effect during the critical season is still present. Wealthy farmers demand more water per tree during the critical season than poor farmers who have the same agricultural products (here, apricots).

Table 4: Demand for Water per Tree and Urban Real Estate.

| Number of units bought per tree              | (1)                   | (2)                | (3)                   | (4)                   |
|--|-----------------------|--------------------|-----------------------|-----------------------|
| High urban real estate                       | 0.0131***<br>(0.0042) | 0.0073<br>(0.0044) | 0.0066<br>(0.0044)    | 0.0017<br>(0.0047)    |
| (High urban real estate) x (Critical season) |                       |                    | 0.0374***<br>(0.0091) | 0.0315***<br>(0.0094) |
| Covariates                                   | No                    | Yes                | No                    | Yes                   |
| Number of observations                       | 14,448                | 14,448             | 14,448                | 14,448                |

Notes: All regressions are OLS specifications. The sample is restricted to farmers who only grow apricots. The dependent variable is the number of units bought by each individual farmer during a given week per tree. “High urban real estate” is a dummy variable that equals 1 if the value of urban real estate of the farmer is above the median. “Critical season” is a dummy that equals one if the observation belongs to a week during the critical season. “Covariates” are the price paid by farmer in the auction, the amount of rainfall during the week of irrigation, and the farmer’s soil moisture level. Standard errors in parentheses. \*  $p < 0.10$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ .

Figure 1: Seasonal Stages for “Búlida” Apricot trees.

|          |           |              |     |     |             |     |      |     |     |          |     |
|----------|-----------|--------------|-----|-----|-------------|-----|------|-----|-----|----------|-----|
| JAN      | FEB       | MAR          | APR | MAY | JUN         | JUL | AUG  | SEP | OCT | NOV      | DEC |
| DORMANCY | FLOWERING | FRUIT GROWTH |     |     | POSTHARVEST |     |      |     |     | DORMANCY |     |
|          |           | STAGE I      | II  | III | EARLY       |     | LATE |     |     |          |     |

Notes: *Source*: Pérez-Pastor *et al.* (2009).

**Water Demand and Apricot Trees.** Figure 1 displays the seasonal stages of the typical apricot tree that is cultivated in Mula, the *búlida* apricot. These trees need the most water during the late fruit growth (stages II and III) and the early post harvest (EPH). This defines the “critical” irrigation season for apricots trees (see Torrecillas *et al.* 2000 for details). Stage III corresponds to the period when the tree “transforms” water into fruit at the highest rate. The EPH period is important because of the hydric stress the tree suffers during the harvest (see Pérez-Pastor *et al.* 2009 for further details).

The top panel in Figure 2 shows the effect of weather seasonality on auction water prices. The figure displays the average weekly prices of water and the average weekly rainfall in Mula. The shaded area corresponds to the critical season as defined above. The price of water increases substantially during the critical season because (1) apricots, along with other products cultivated in the region, require more irrigation during this season, increasing the

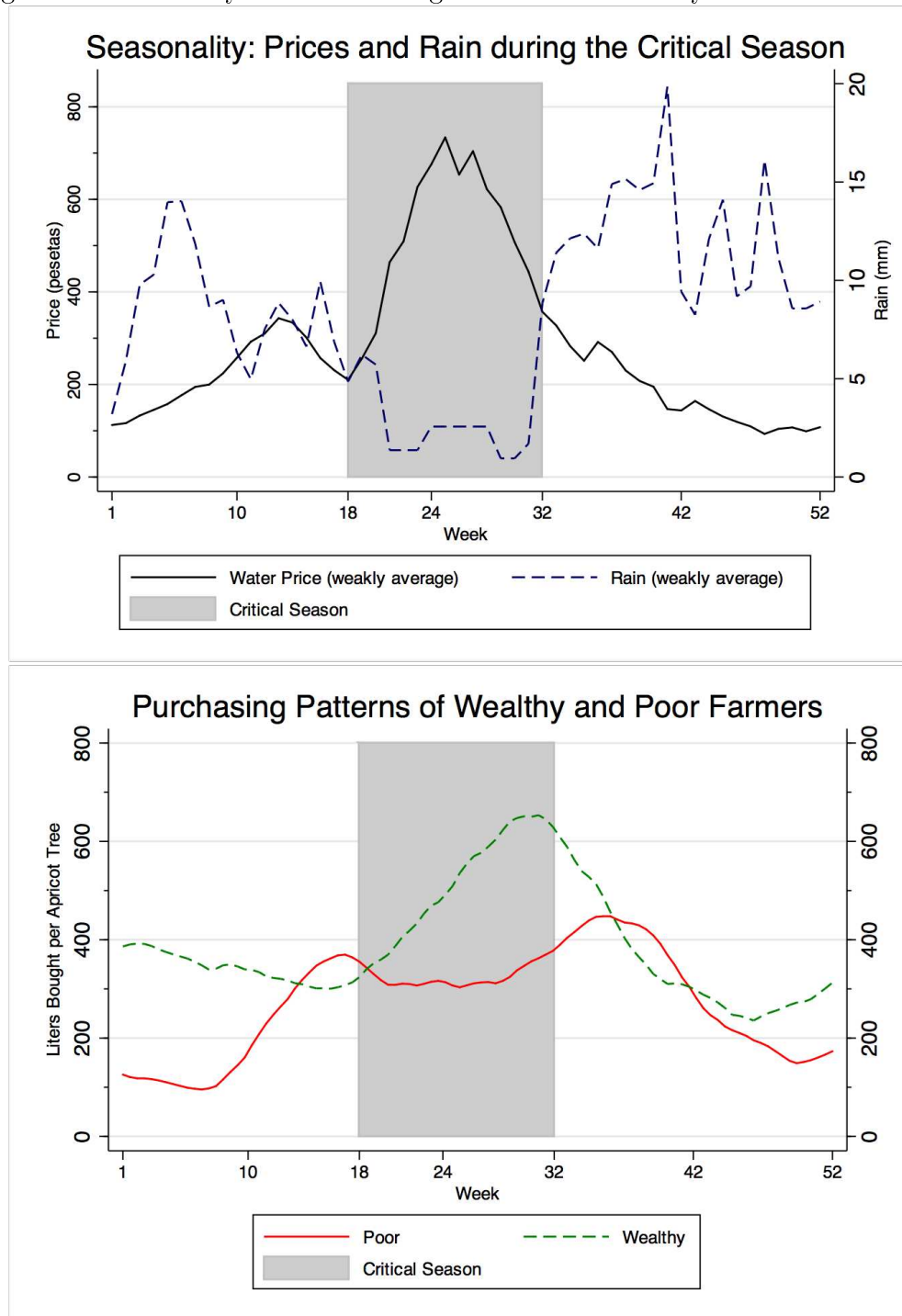
demand for water in the auction; and (2) weather seasonalities in southern Spain generate less rainfall during these months (top panel in Figure 2).

The bottom panel in Figure 2 shows the purchasing patterns of wealthy and poor apricot farmers. The figure displays the average liters per tree that each farmer purchased in the auction. Wealthy farmers—who are not liquidity constrained—demand water as predicted by Figure 1. Wealthy farmers strategically delay their purchases and buy water during the critical season, when the apricot trees most need water. On the other hand, poor farmers—who may be liquidity constrained—display a bimodal purchasing pattern for water. The first peak occurs before the critical season, when water prices are relatively low (see top panel). Poor farmers buy water before the critical season because they anticipate that they may not be able to afford water during the critical season due to increased auction prices. A fraction of this water will evaporate, but the rest will remain in the soil’s moisture of the farmer.

The second peak occurs after the critical season, when water prices are relatively low again. After the critical season the moisture level on the plots of the poor farmers is low if they had not been able to buy sufficient water during the critical season. Thus, the poor farmers buy water after the critical season to prevent the trees from withering. This purchasing pattern for the poor farmers (high purchases before and after the critical season, and low purchases during the critical season) can be explained with a model that includes seasonality, storability and liquidity constraints. That is what we do in section 3.

To identify LC we assume that wealthy and poor apricot farmers have the same production function. Although this assumption is untestable, we provide auxiliary evidence to support it in Table 5. This table shows that among farmers who grow only apricot trees, wealthy farmers obtain greater revenue than poor farmers. However, if a farmer grows another agricultural product in addition to apricot trees (*e.g.* oranges), then there are no substantial differences between wealthy and poor farmers. Moreover, revenue for oranges does not depend on the wealth of the farmer either. This is because oranges are harvested in

Figure 2: Seasonality and Purchasing Patterns of Wealthy and Poor Farmers.



Notes: The top panel displays: (1) the average weekly prices of water paid in the auction (left vertical axis), (2) the average weekly rain in Mula (right vertical axis), and (3) the critical season for apricots trees as defined in Figure 1 (shaded area). The bottom panel displays the average liters bought per farmer and per tree disaggregated by wealthy and poor farmers. A farmer is defined as wealthy if the value of urban real estate of the farmer is above the median. A farmer is defined as poor if the value of urban real estate of the farmer is below the median. The shaded area in the bottom panel displays the critical season (identical as in the top panel).

winter, unlike apricots that are harvested in the summer when water prices are high. Water prices during the oranges' harvest season are low, thus LC play no role. Farmers who grow both apricots and oranges use the cash obtained in winter from the orange harvest to buy water for the apricots in the summer. Similarly, they use the cash obtained from the apricot harvest to buy water for the oranges in winter. Hence, they are not affected by LC. Farmers who only grow apricots do not have access to this “cash smoothing mechanism” and are therefore affected by LC.<sup>19</sup>

The results in Table 5 provide evidence of both LC and low productivity heterogeneity. Column (1) shows that the average revenue per apricot tree for farmers growing only apricots is much smaller for poor farmers. Column (2) shows that the revenue per orange tree is similar for poor and wealthy farmers. Column (3) shows that the same is true among the farmers who grow apricots and other crops. The same is true for lemons and peaches. We interpret these results as evidence that the differences in revenue observed among the farmers who only grow apricots are due to differences in input utilization (*e.g.* water) used by wealthy and poor farmers, and not due to differences in their production function.<sup>20</sup>

### 3 The Econometric Model

In this section, we present the econometric model that allows us to compute the welfare under auctions and under quotas. Computing the welfare would be straightforward with output data (*i.e.* production data) before and after the institutional change. But this output data is not available. So we use detailed input data (units of water purchased, rainfall amount, number of apricot trees, *etc.*) along with the apricot production function (that transforms these inputs into apricots) to compute the output before and after the

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<sup>19</sup>Results for other crops harvested in the summer such as lemons and peaches are similar to those for apricots.

<sup>20</sup>When looking at the revenue per tree for wealthy farmers, farmers growing only apricot trees have a greater revenue than farmers growing also other crops. The reason behind this result is that wealthy farmers growing only apricot trees have a lower average number of trees (72 trees) than farmers growing also other crops (109 trees). This is due to diseconomies of scale. The number of trees for poor farmers growing only apricot trees is 73, thus diseconomies of scale are playing no role when comparing poor and wealthy farmers.



Table 5: Revenue per tree in 1954 for different crops.

| Revenue per tree       | Apricot-only<br>(1) | Orange-other<br>(2) | Apricot-other<br>(3) | Lemon-other<br>(4) | Peach-other<br>(5) |
|------------------------|---------------------|---------------------|----------------------|--------------------|--------------------|
| Total                  | 134.21              | 125.13              | 124.70               | 112.92             | 51.81              |
| Low urban real estate  | 105.47              | 131.65              | 129.69               | 120.37             | 47.09              |
| High urban real estate | 162.94              | 119.48              | 119.23               | 105.93             | 55.58              |
| Number of farmers      | 24                  | 322                 | 239                  | 64                 | 45                 |

Notes: Own elaboration from the 1955 Agricultural census. “Apricot-only” refers to the revenue generated by apricot trees for farmers that only grow apricot trees. “Apricot-other” refers to the revenue generated by apricot trees for farmers who grow apricot and other trees. “Lemon-other” refers to the revenue generated by lemon trees for farmers who grow lemon and other trees. “Peach-other” refers to the revenue generated by peach trees for farmers who grow peach and other trees. “Orange-other” refers to the revenue generated by orange trees for farmers who grow orange and other trees. “High urban real estate” is a dummy variable that equals 1 if the value of urban real estate of the farmer is above the median.

institutional change. We proceed in three steps. First, we present the econometric model. The econometric model uses the apricot production function obtained from the agricultural engineering literature and incorporates three features of our setting: storability, liquidity constraints (LC), and seasonality. Second, we estimate the model using the input data. Finally, we use the estimated model to compute the output under auctions and quotas. This allow us to perform the counterfactual analysis of welfare (*i.e.* production of apricot) before and after the institutional change.

We now describe the econometric model. The economy consists of  $N$  farmers, indexed by  $i$ , and one auctioneer. Water increases the farmer’s soil moisture level. So, from the point of view of the farmer, there are two goods in the economy: moisture,  $M$ , measured in liters per square meter ( $l/m^2$ ) and money,  $\mu$ , measured in *pesetas*. Time is denoted by  $t$ , the horizon is infinite, and the discount between periods (weeks) is  $\beta \in (0, 1)$ . Demand is seasonal, hence some of the functions depend on the season. We denote the season by  $w_t \in \{1, 2, \dots, 52\}$ , representing each of the 52 weeks of any given year. In each period, the supply of water in the economy is exogenous.

Farmers only get utility for water consumed during the critical season. Water is an intermediate good. Hence, utility refers to the farmer’s profit and is measured in *pesetas*,

not in *utils*. Water bought in any period can be carried forward into the next period, but it “evaporates” as indicated by the evolution of the soil moisture in equation 1 (*i.e.* water “depreciates” at some rate  $\delta \in (0, 1)$ ).

Farmers’ preferences over moisture and money are represented by  $u(j_{it}, M_{it}, w_t, \mu_{it}, \varepsilon_{ijt}; \gamma, \sigma_\varepsilon, \chi) = h(j_{it}, M_{it}, w_t; \gamma) + \varepsilon_{ijt} - p_t j_{it} - \zeta + \mu_{it}$ , where  $h(\cdot)$ , is the apricot production function (common to all farmers) that is strictly increasing and concave in the moisture level of the farmer,  $M_{it}$ ; <sup>21</sup>  $\varepsilon_{ijt}$  is an additive productivity shock to farmer  $i$  in period  $t$  given that the farmer bought  $j_t$  units of water;  $p_t$  is a scalar that represents the price of water in the auction in period  $t$  (common to all farmers);  $j_{it} \in \{0, 1, \dots, J\}$ , is the number of units that farmer  $i$  buys in period  $t$ ;  $\mu_{it}$  is the amount of cash that farmer  $i$  has in period  $t$ ; and  $(\gamma, \sigma_\varepsilon, \chi)$  is a vector of parameters (to be estimated) that we describe below. We require that  $(\mu_{it} - p_t j_{it}) \geq 0$ ,  $\forall j_{it} > 0$  (*i.e.* limited liability). Finally,  $\zeta_j$  is a choice-specific component of the irrigation. The intuition for including  $\zeta$  is that the farmer might have to incur an additional cost when irrigating. This disutility could result, for example, if the farmer hires a laborer to help with irrigation.

Farmers in the economy differ from each other in two ways. First, they differ in their productivity shock,  $\varepsilon_{ijt}$ . Second, they differ in their wealth levels,  $\mu_{it}$ . We describe the evolution of the wealth level below. Both  $\varepsilon_{it}$  and  $\mu_{it}$  are private information.

## State Variables

There are six state variables in the model:

- $M_{it}$  (deterministic, measured in  $l/m^2$ ): is the moisture level of the plot. It represents the amount of water accumulated in the farmer’s plot.
- $w_t$  (deterministic): is the weekly seasonal effect. Its support is  $\{1, 2, \dots, 51, 52\}$ .
- $p_t$  (random, measured in *pesetas*): is the price for each unit of water during week  $t$ .

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<sup>21</sup>For the estimation we use a equation 5 (discussed below) obtained from the agricultural engineering literature. See appendix A.2 for details.

- $r_t$  (random, measured in  $l/m^2$ ): is the amount of rain that fell on the town during period  $t$ .
- $\epsilon_{it} \equiv (\epsilon_{i0t}, \dots, \epsilon_{iJt})$  (random): is a choice specific component of the utility function.
- $\mu_{it}$ : represents the amount of cash that the individual has at period  $t$ .

## Evolution of the State Variables

**Moisture.** Trees on a farmer’s plot die if the soil moisture level falls below the permanent wilting point,  $PW$ , which is a scalar obtained from the agricultural engineering literature. So each farmer  $i$  must satisfy the constraint  $M_{it} \geq PW \forall t$ . The law of motion for the moisture,  $M_{it}$ , is given by:<sup>22</sup>

$$M_{it} = \min \left\{ M_{i,t-1} + r_t + \frac{j_{it} \cdot 432,000}{area_i} - ET(M_{it}, w_t), FC \right\}, \quad (1)$$

where  $r_t$  is the amount of rainfall (measured in  $mm$ ) in Mula during period  $t$ ;  $j_{it}$  is the number of units purchased by farmer  $i$  in period  $t$ ; 432,000 is the number of liters in each unit of water;  $area_i$  is the farmer’s plot area (measured in square meters);  $ET(M_{it}, w_t)$  is the adjusted evapotranspiration in period  $t$ ; and  $FC$  is the full capacity of the farmer’s plot. Moisture and seasonality are the main determinants of water demand. The moisture level increases with rain and irrigation, and decreases over time as the accumulated water “evaporates” (evapotranspiration). Although the moisture level is not observable, both rain and irrigation are observable. We use equation 1 to compute the moisture level.

**Weekly Seasonal Effect.** The evolution of the weekly season is mechanical:

$$w_t = \begin{cases} w_{t-1} + 1 & \text{if } w_{t-1} < 52 \\ 1 & \text{if } w_{t-1} = 52 \end{cases}. \quad (2)$$

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<sup>22</sup>We follow the literature in agricultural engineering to compute the moisture. See appendix A.2 for details.

Farming is a seasonal activity. Each crop has different water requirements, depending on the season. The apricot water requirement is captured by the production function,  $h(j_{it}, M_{it}, w_t)$ . Since the market for water has a weekly frequency, we have a state variable with a different value for every week of the year.

**Price of Water and Rainfall.** The main determinant of both water auction prices and rainfall is seasonality. Our unit of analysis is a week, so we work with average weekly prices and average weekly rainfall. Average weekly prices and average weekly rainfall vary substantially across weeks of the year (see Figure 2). However, for a given week, the variation of prices and rainfall across years is very low (see Donna and Espín-Sánchez, 2015, for details regarding the evolution of prices in the auctions).

We model the evolution of prices and rainfall to capture these empirical regularities. Our data covers a sample of 12 years. We assume that, holding fixed the week of the year, farmers jointly draw a price-rain pair,  $(p_t, r_t)$ , among the 12 pairs (*i.e.* the 12 years of the same week) available in the data with equal probability.<sup>23</sup>

**Productivity Shock.** We assume that the productivity shocks  $\varepsilon_{ijt}$  are drawn *i.i.d.* (across individuals and over time) from a Gumbel distribution with CDF  $F(\varepsilon_{it}; \sigma_\varepsilon) = e^{-e^{-\varepsilon_{it}/\sigma_\varepsilon}}$ , where  $\sigma_\varepsilon$  is a parameter to be estimated. The variance of this distribution is given by  $\sigma_\varepsilon^2 \pi^2/6$ . The higher the value of the parameter  $\sigma_\varepsilon$ , the more heterogeneous the distribution of productivity.

**Cash Holdings.** Farmer  $i$ 's cash in period  $t$ ,  $\mu_{it}$ , evolves according to:

$$\mu_{it} = \mu_{i,t-1} - p_{t-1}j_{i,t-1} + \Phi_t(re_i; \phi) + \eta_{it} + \nu_{it}, \quad (3)$$

where  $\Phi_t(re_i; \phi) = \phi_{i0} + \phi_1 re_i$  captures the (weekly) cash flow function derived from the

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<sup>23</sup>We obtain similar results by estimating the joint distribution of prices and rain nonparametrically conditional on the week of the year, and then drawing price-rain pairs from this distribution, conditional on the week of the year. Results are available upon request.

real estate value  $\phi_{re_i}$  minus individual  $i$ 's weekly consumption that is constant over time,  $\phi_{i0}$ ;  $\eta_{it}$  is the revenue the farmer obtains when she sells the harvest (we present the revenue below in equation 8), and  $\nu_{it}$  is are idiosyncratic financial shock that are drawn *i.i.d.* (across individuals and over time) from a normal distribution. The revenue  $\eta_{it}$  is equal to 0 all weeks of the year, except the week after the harvest, when farmers sell their products and collect revenue. (See appendix B for details.)

## Value Function

The expected discounted utility of farmer  $i$  at  $t = 0$  is then:

$$\begin{aligned} \mathbb{E} \left[ \sum_{t=0}^{\infty} \beta^t [h(j_{it}, M_{it}, w_t; \gamma) + \varepsilon_{ijt} - p_t j_{it} - \zeta + \mu_{it}] \right] \\ \text{s.t. } M_{it} \geq PW \\ \text{s.t. } j_{it} p_t \leq \mu_{it}, \quad j_{it} > 0 \end{aligned} ,$$

subject to the evolution of the state variables as described above. The expectation is taken over  $r_t$ ,  $p_t$ ,  $\varepsilon_{ijt}$ , and  $\nu_{it}$ . Note that for wealthy farmers the constraint  $j_{it} p_t \leq \mu_{it}$  is not binding. Then, the value function is:

$$\begin{aligned} V(M_{it}, w_t, p_t, r_t, \mu_{it}, \varepsilon_{ijt}) \equiv \max_{j_{it} \in \{0, 1, \dots, J\}} \{h(j_{it}, M_{it}, w_t; \gamma) + \varepsilon_{ijt} - p_t j_{it} - \zeta + \mu_{it} + \\ + \beta \mathbb{E} [V(M_{i,t+1}, \mu_{i,t+1}, w_{t+1}, p_{t+1}, r_{t+1}, \varepsilon_{i,t+1}) | M_{it}, w_t, p_t, r_t, \mu_{it}, j_{it}]\} \\ \text{s.t. } M_{it} \geq PW \\ \text{s.t. } j_{it} p_t \leq \mu_{it}, \forall j_{it} > 0 \end{aligned} , \quad (4)$$

subject to the evolution of the state variables as described above.

## The Apricot Production Function

The production function of the apricot tree is given by Torrecillas *et al.* (2000):

$$h(M_{t-1}, w_t; \gamma) = [\gamma_1 \cdot (M_{t-1} - PW) \cdot KS(M_t) \cdot Z_1(w_t) + \gamma_2 \cdot (M_{t-1} - PW) \cdot KS(M_t) \cdot Z_2(w_t)] \cdot area_i, \quad (5)$$

where  $h(M_{t-1}, w_t; \gamma)$  is the harvest at period  $t$ ;  $\gamma \equiv (\gamma_1, \gamma_2)$  is a parameter vector that measures the transformation rate of the production function;  $area_i$  is the size of the land ( $m^2$ ) that farmer  $i$  owns,  $KS(M_t)$  is the hydric stress coefficient (see appendix A.2),  $Z_1(w_t)$  is a dummy variable that equals 1 during weeks 18-23 and 0 otherwise:

$$Z_1(w_t) = \begin{cases} 1 & \text{if } 18 \leq week \leq 23 \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

and  $Z_2(w_t)$  is a dummy variable that equals 1 during weeks 24-32 and 0 otherwise:

$$Z_2(w_t) = \begin{cases} 1 & \text{if } 24 \leq week \leq 32 \\ 0 & \text{otherwise} \end{cases}. \quad (7)$$

The characterization of  $\gamma$  is a direct application of results from the agricultural engineering literature (Torrecillas *et al.*, 2000; Pérez-Pastor *et al.*, 2009). The parameter  $\gamma_1$  measures the transformation rate of fruit during the fruit growth season. The parameter  $\gamma_2$  measures the recovery of the tree during the early post-harvest stress season. Both parameters are measured in *pesetas* per *liter*.<sup>24</sup>

Given this payoff function, we can compute the farmer's revenue in a given year:

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<sup>24</sup>The production function measures the production in *pesetas*. But the actual price at which the production is sold is determined in the output market. We do not have data on the price at which this production is sold. So we recover the revenue of the farmers up to this constant (the common price at which the production of all farmers is sold in apricot market). This price only shifts the the revenue function of all (wealthy and poor) farmers. So it does not affect our welfare analysis.

$$Revenue_t = \sum_{w_t=18}^{23} \gamma_1 \cdot (M_{t-1} - PW) \cdot KS(M_t) \cdot area_i + \sum_{w_t=24}^{32} \gamma_2 \cdot (M_{t-1} - PW) \cdot KS(M_t) \cdot area_i. \quad (8)$$

## 4 Estimation

We estimate the parameters of the model in two stages. In the first stage, we estimate the parameters that characterize demand,  $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$ , using data from wealthy farmers, excluding the data of poor farmers who may be liquidity constrained. In the second stage, we estimate the vector of financial parameters,  $\chi$ , using the estimated parameters from the first stage,  $\hat{\Theta}$ . The exclusion restriction for the second stage is that poor farmers have the same production function as wealthy farmers, up to an idiosyncratic shock. Thus, we assume that there is no unobserved heterogeneity that affects the production function of wealthy and poor farmers differently.

### 4.1 First Stage: Demand Estimates

In the first stage, we construct a two-step conditional choice probability (CCP) estimator (Hotz and Miller, 1993) to estimate the parameters that characterize demand.

**Step 1.** In the first step we compute transition probability matrices for the following state variables: moisture, week, price, and rain. As described above, the productivity shocks  $\varepsilon_{ijt}$  are assumed to be *i.i.d.* Gumbel, so they can be integrated analytically. The transition probability of the cash holdings is estimated in the second stage. Moisture is a continuous variable and its evolution over time depends on both the farmers' decisions to buy water and rainfall. Therefore, certain values of moistness are never reached in the sample, even when their probability of occurrence is nonzero. To estimate demand, however, we need to integrate the value function for each possible combination of the state variables in the state space. Thus, we first estimate the CCP using the values (of the state space) reached in the

sample. Then we use the CCP estimator to predict the CCP on the values (of the state space) unreached in the sample.<sup>25</sup> (See appendix B for details.)

**Step 2.** In the second step we build an estimator similar to one by proposed by Hotz et. al (1994). We use the transition matrices to forward simulate the value function from equation 4. This gives us the predicted CCP by the model as a function of the parameters  $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$ . The estimated parameters are obtained by minimizing the distance between the CCP (that are a function of the data and are obtained in the first step) and predicted CCP (that are a function of the parameters). The exclusion restriction for the first stage is that wealthy farmers are not liquidity constrained.

## 4.2 Second Stage: Financial Parameters

In the second stage, we estimate the financial parameters,  $\chi$ , by maximum likelihood. In the data we only observe whether the poor farmer buys water or not, in addition to the number of units purchased. When a farmer does not buy water, we do not know whether it is because the farmer does not demand water and is not liquidity constrained, or whether the farmer is liquidity constrained. That is, for the poor farmers, the dependent variable is censored. So we compute the probability that a poor farmer  $i$  is liquidity constrained using the estimates from the first stage. The intuition behind this is that farmers are heterogeneous in two dimensions: their productivity and liquidity constraints. Thus, a rich farmer and a poor farmer who have the same number of apricot trees only differ in the idiosyncratic productivity shock and their cash flow. Using the estimated production function parameters from the first stage (*i.e.* using the data of the wealthy farmers), we can compute the probability that the poor farmer is liquidity constrained using the distribution of the idiosyncratic financial shock and treating the farmer's decision variable as a censored variable. This allows us to write the likelihood of a poor farmer being liquidity constrained (see appendix B.2 for details). The

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<sup>25</sup>We estimate the CCP both non-parametrically (using kernel methods to smooth both discrete and continuous variables) and parametrically (using a logistic distribution, *i.e.*, a multinomial logit regression).



exclusion restriction for the second stage is that poor farmers have the same production function as the wealthy farmers (*i.e.* no unobserved heterogeneity).

## 5 Estimation Results

In this subsection, we present the estimation results of the econometric model under different specifications.

### 5.1 First Stage Results: Demand Estimates

Table 6 displays the estimation results from the first stage of the model from Section 4 (demand parameters  $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$  from equation 4) using the estimation procedure from Section 5. We use the apricot production function as outlined in equation 5.

We present four sets of specifications. In columns 1 to 3 the scale parameter of the Gumbel distribution (*i.e.* distribution of idiosyncratic productivity) is restricted to  $\sigma_\varepsilon = 1$ . The higher the parameter  $\sigma_\varepsilon$ , the higher the variance of the distribution of idiosyncratic productivity. When  $\sigma_\varepsilon = 1$ , the distribution of idiosyncratic productivity is a standard Gumbel, restricting the heterogeneity of the idiosyncratic productivity. In addition, in columns 1 to 3 we perform the estimation with only one type of farmer who has the median number of trees from the sample (“Area heterogeneity: No”). This means that when we forward simulate the value function (as outlined in subsection 4.1),  $area_i$  from equation 5 is set to the median area for all individual farmers  $i$ . In column 1 we restrict the transformation rate on-season ( $24 \leq week \leq 32$ ) to  $\gamma_1 = 0$ . The estimated transformation rate pre-season ( $18 \leq week \leq 23$ ) is  $\hat{\gamma}_0 = 0.76$ . In column 2 we restrict  $\hat{\gamma}_0 = \hat{\gamma}_1$ . The overall transformation rate (*i.e.*  $\hat{\gamma}_0 \times \mathbf{1}(18 \leq week \leq 23) + \hat{\gamma}_1 \times \mathbf{1}(24 \leq week \leq 32)$ ) is similar in magnitude to column 1. In column 3, there are no restrictions on the transformation rate. The irrigation cost represents the cost in *pesetas* that a farmer incurs every time she irrigates.

In the second set of estimates (columns 4 to 6) we repeat the previous specifications,

Table 6: Structural Estimates

| Estimates   | (1)  | (2)   | (3)                            | (4)                  | (5)                               | (6)                 | (7)  | (8)   | (9)                            | (10)                 | (11)                              | (12)                |
|---|--|---|--------------------------------|----------------------|-----------------------------------|---------------------|--|---|--------------------------------|----------------------|-----------------------------------|---------------------|
| Transformation rate<br>pre-season: $\hat{\gamma}_0$<br>( $18 \leq week \leq 23$ ) | 0.7589<br>(0.1136)                                     | 0.3241<br>(0.1356)  | 0.3962<br>(0.1927)             | 0.7145<br>(0.0983)   | 0.3241<br>(0.0739)                | 0.3963<br>(0.1739)  | 0.7560<br>(0.1172)                                     | 0.3281<br>(0.1203)  | 0.3933<br>(0.1203)             | 0.7560<br>(0.1029)   | 0.3281<br>(0.0998)                | 0.3641<br>(0.1145)  |
| Transformation rate<br>on-season: $\hat{\gamma}_1$<br>( $24 \leq week \leq 32$ )  | 0<br>—   | 0.3241<br>(0.1356)  | 0.2704<br>(0.0710)             | 0<br>—               | 0.3241<br>(0.0739)                | 0.2703<br>(0.1278)  | 0<br>—   | 0.3281<br>(0.1203)  | 0.2782<br>(0.1147)             | 0<br>—               | 0.3281<br>(0.0998)                | 0.2763<br>(0.1157)  |
| Irrigating cost: $\hat{\zeta}$  | 10.0839<br>(2.7793)                                    | 10.2324<br>(2.3870)   | 10.2431<br>(1.1912)            | 10.1003<br>(2.1357)  | 10.2279<br>(2.2333)               | 10.2384<br>(1.2836) | 10.0863<br>(2.9592)                                    | 10.2273<br>(2.8628)   | 10.2402<br>(1.2434)            | 10.0821<br>(2.0229)  | 10.2229<br>(2.0653)               | 10.2528<br>(1.3831) |
| Scale parameter of<br>Gumbel distribution: $\hat{\sigma}_\varepsilon$             | 1<br>—   | 1<br>—  | 1<br>—                         | 1.0967<br>(0.4961)   | 1.1767<br>(0.3586)                | 1.1778<br>(0.3716)  | 1<br>—   | 1<br>—  | 1<br>—                         | 1.0959<br>(0.4892)   | 1.1575<br>(0.3253)                | 1.1728<br>(0.3684)  |
| Constraints   | $\hat{\gamma}_1 = 0$<br>$\hat{\sigma}_\varepsilon = 1$ | $\hat{\gamma}_0 = \hat{\gamma}_1$<br>$\hat{\sigma}_\varepsilon = 1$ | $\hat{\sigma}_\varepsilon = 1$ | $\hat{\gamma}_1 = 0$ | $\hat{\gamma}_0 = \hat{\gamma}_1$ | None                | $\hat{\gamma}_1 = 0$<br>$\hat{\sigma}_\varepsilon = 1$ | $\hat{\gamma}_0 = \hat{\gamma}_1$<br>$\hat{\sigma}_\varepsilon = 1$ | $\hat{\sigma}_\varepsilon = 1$ | $\hat{\gamma}_1 = 0$ | $\hat{\gamma}_0 = \hat{\gamma}_1$ | None                |
| Area heterogeneity  | No   | No  | No                             | No                   | No                                | No                  | Yes  | Yes   | Yes                            | Yes                  | Yes                               | Yes                 |

Notes: Standard errors in parenthesis. See subsection 6.1 for details about this table.

allowing the distribution of idiosyncratic productivity to have a different scale parameter, which we estimate (*i.e.* we estimate the parameter  $\sigma_\varepsilon$ ). The results are similar to the first set of specifications.

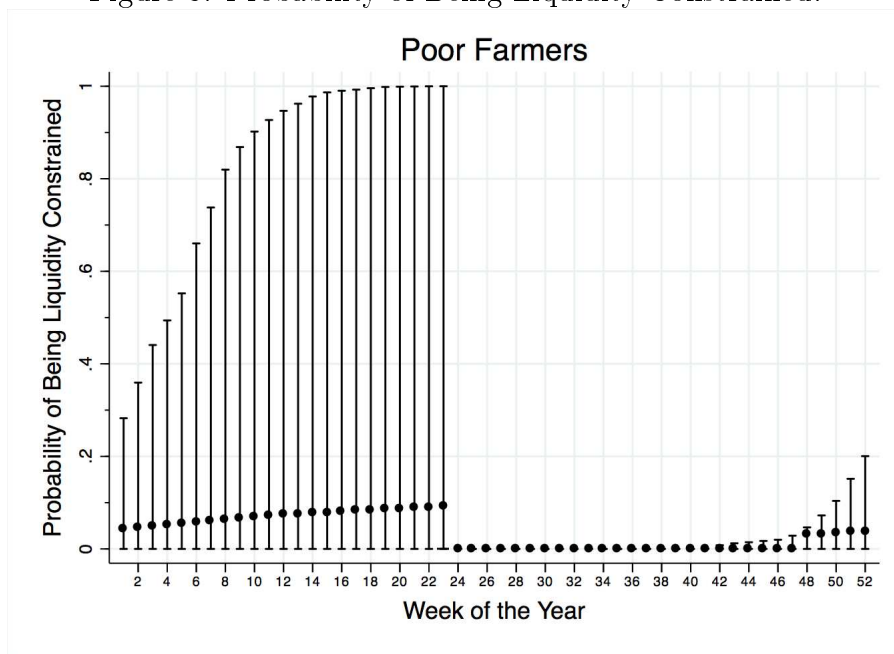
In columns 7 to 9 we perform the estimation with 10 different discrete types of farmers, that only differ in the area (“Area heterogeneity: Yes”). The area of each type correspond to the number of trees of the wealthy farmers in the data (there are 12 wealthy farmers in the data, but there are two pairs farmers with the same area). Each discrete type has the same probability. This means that when we forward simulate the value function (as outlined in subsection 4.1), the value of  $area_i$  from equation 5 is drawn uniformly at random from a distribution with discrete support at the points  $\{area_1, area_2, \dots, area_{10}\}$ . In Table 6 we report the mean  $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$  across types. The results are similar to the first set of specifications.

Finally, the fourth set of estimates (columns 10 to 12) allow for both: (1) a different scale parameter for the distribution of idiosyncratic productivity ( $\sigma_\varepsilon$ ), and (2) farmer heterogeneity in terms of the area.

## 5.2 Second Stage Results: Financial Parameter Estimates

We estimate the financial parameters,  $\chi$ , by maximum likelihood using a standard censored model. See appendix B.2 for details. Table A1 in the in the online appendix displays the estimates of the financial parameters. We use these estimates to compute the probabilities that a given farmer is liquidity constrained in a given week. Figure 3 displays the empirical distribution (among the poor farmers) of the Probability of being Liquidity Constrained (PLC).  $PLC_i = \mathbb{P}(p_{t,jit} > \mu_{it})$  where  $i$  index the poor farmers. Week 24 is the harvest (*i.e.* when the farmers collect their cash revenue). As expected, the PLC is close to zero after week 24 (*i.e.* after the harvest). This is because the farmers has just collected the cash revenue and the water need of the trees is low. However, for weeks 1-23 (*i.e.* before the harvest), there is substantial heterogeneity among poor farmers: some of the poor farmers

Figure 3: Probability of Being Liquidity Constrained.



Notes: Week 24 is the harvest (*i.e.* when the farmers collect their cash revenue). Each vertical line displays the empirical distribution (among the poor farmers) of the Probability of being Liquidity Constrained (PLC).  $PLC_i = \mathbb{P}(p_{tj_{it}} > \mu_{it})$  where  $i$  index the poor farmers (see appendix B.2 for details). Each week of the year displays a vertical line with: (1) an upper whisker that represents the maximum PLC (that corresponds to the farmer who has the maximum PLC among the poor farmers); (2) a black circle marker that represents the mean PLC (the mean PLC among the poor farmers); and (3) a lower whisker that represents the minimum PLC (that corresponds to the farmer who has the minimum PLC among the poor farmers). If the maximum PLC coincides with the minimum PLC, then the figure shows only a dot (which corresponds to the mean too).

are liquidity constrained with probability one, while others are not liquidity constrained. The weeks before the harvest are the weeks farthest away from the last harvest and the weeks when the farmers need the water the most. The mean PLC for weeks 1-23 lies between 5% and 10%.

## 6 Welfare

In this section we use the estimated demand system (from the first stage) to compare the welfare under auctions, quotas, and the first-best (*FB*) allocation.

## 6.1 Welfare Measures

In this subsection we describe how we construct the welfare measures. Given rainfall and the allocation of water among the farmers, the yearly average revenue per tree for farmer  $i$  is given by:

$$Revenue_i = \frac{1}{\# \text{ trees}_i} \frac{1}{T} \sum_{t=1}^T [Revenue_{it}] = \frac{1}{\# \text{ trees}_i} \frac{1}{T} \sum_{t=1}^T \left[ \sum_{w_t=1}^{52} h(M_{i,t-1}, w_t) - (\zeta_j) \right] \quad (9)$$

Note that we do not take into account the expenses in water because we are interested in welfare measures (*i.e.* transfers are not taken into account).

Welfare is defined as follows:

$$Welfare_i = \frac{1}{\# \text{ trees}_i} \frac{1}{T} \sum_{t=1}^T [Welfare_{it}] = \frac{1}{\# \text{ trees}_i} \frac{1}{T} \sum_{t=1}^T \left[ \sum_{w_t=1}^{52} h(M_{i,t-1}, w_t) - (\zeta_j + \epsilon_{ijt}) \right] \quad (10)$$

The only difference between revenue in equation 9 and welfare in equation 10 is the choice specific unobservable component,  $\epsilon_{ijt}$ . Since the error term  $\epsilon_{ijt}$  is choice-specific, the relevant elements are differences in  $\epsilon_{ijt}$  across choices, and not  $\epsilon_{ijt}$ . For example, in the case in which  $J = 1$ , the farmer chooses whether to buy 1 unit or not to buy. The farmer balances the difference in utility between buying or not, considering both the observable and unobservable (for the econometrician) components. The probability of a farmer buying water increases with the expectation of the difference in  $\epsilon_{ijt}$ , *i.e.*, with  $\mathbb{E}[\epsilon_{i1t} - \epsilon_{i0t}]$ .

By construction, the unconditional mean of the differences in the error term is zero. Hence, in the quotas system, since the farmers cannot choose when to irrigate, the expectation of the difference in the error term is zero, *i.e.*,  $\mathbb{E}[\epsilon_{i1t} - \epsilon_{i0t}] = 0$ . However, in the auction system, farmers choose when to irrigate and the conditional expectation is nonzero. Farmers are more likely to irrigate when their unobserved utility of irrigation is positive,

*i.e.*,  $\hat{\epsilon}_{i1t} > \hat{\epsilon}_{i0t}$ . This implies that under the auction system:  $\mathbb{E}[\epsilon_{i1t} - \epsilon_{i0t} | j = 1] > 0$  and  $\mathbb{E}[\epsilon_{i0t} - \epsilon_{i1t} | j = 0] > 0$ . In other words, in the auction system, gains from trade are realized. In the model, gains from trade are translated into the timing of irrigation. Farmers “trade” with each other in order to irrigate at their preferred time. For this reason, welfare is always greater than revenue under the auction system.

We compute the welfare for the following allocation mechanisms: (1) Auctions using complete units,  $Ac$ , wherein complete water units are assigned to the farmer who bought them as observed in the data; (2) Quotas with random assignment of complete units,  $Qc$ , wherein every time we observe a farmer purchase a unit of water under the auction system, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among all farmers; (3) Quotas with sequential assignment of complete units,  $QcX\%$ , wherein every time we observe a farmer purchased a unit of water under the auction system, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among the  $X\%$  of farmers who did not receive irrigation the longest;<sup>26</sup> (4) Quotas with random assignment of fractional units,  $Qf$ , wherein every time we observe a farmer purchased a unit of water under the auction system, all farmers are allocated a fraction

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<sup>26</sup>That is, we keep track of when was the last time that each farmer irrigated under the quotas system. Then, to allocate a unit of water on week  $t$ , we only consider the subset of farmers whose last irrigation was farthest away from  $t$  (this is the subset of farmers who value the water the most). Then we allocate the unit of water uniformly at random (proportional to their amount of land) among this subset of farmers. The value of  $X$  defines how large is this set. For example, if  $X = 100\%$ , then all farmers are included in the set and the unit of water is allocated uniformly at random (proportional to their amount of land) among *all* farmers.

Formally, the subset is defined as follows. Let  $t_i^{Last} < t$  be the last week farmer  $i$  was allocated a unit of water under the quota system. Let  $I$  be the total number of farmers and let  $\mathcal{I}$  be the set of all farmers. Let us index the farmers according to the last time that each farmer irrigated, being farmer  $I$  the one who irrigated in the week closest to  $t$  and being farmer 1 the farmer who irrigated in the week farthest away from  $t$ . Then  $t_1^{Last} \leq t_2^{Last} \leq t_3^{Last} \leq \dots \leq t_I^{Last}$ . (Note that such ranking can always be done and, typically, can be done using several strict inequalities, depending on how many units have been allocated in the past.) Let  $X = x/I \times 100$  for  $x \in 1, 2, \dots, I$ . So given  $X$ , we can compute  $x = X/100 \times I$ . Then, under  $QcX\%$  we allocate the unit of water uniformly at random (proportional to their amount of land) among the subset of farmers  $\tilde{\mathcal{I}}_{X\%} \equiv \{i \in \mathcal{I} : i \leq x, \text{ with } x = X/100 \times I\}$ . For example, if  $I = 10$ ,  $t_1^{Last} \leq t_2^{Last} \leq t_3^{Last} < t_4^{Last} \leq \dots \leq t_{10}^{Last}$ , and  $X = 30\%$ , then  $x = 30/100 \times 10 = 3$  and  $\tilde{\mathcal{I}}_{30\%} = \{1, 2, 3\}$ . So, we allocate the unit of water uniformly at random (proportional to their amount of land) among farmers indexed as 1, 2, and 3. These are the three farmers whose last irrigation was farthest away from  $t$ . In case of ties, we include all tied farmers in the subset  $\tilde{\mathcal{I}}$ . In the previous example, if  $t_1^{Last} \leq t_2^{Last} \leq t_3^{Last} = t_4^{Last} = t_5^{Last} < t_6^{Last} \leq \dots \leq t_{10}^{Last}$ , then  $\tilde{\mathcal{I}}_{30\%} = \{1, 2, 3, 4, 5\}$ .

of that unit (proportional to their amount of land); and (5) the first-best allocation using complete units, *FBC*, wherein every time we observe a farmer purchased a unit of water under the auction system, the complete unit of water is assigned to the farmer who value the water the most. In all cases (*Ac*, *Qc*, *QcX%*, and *FBC*) we compute the welfare measures using the actual allocation of water from the data under the auctions system (*i.e.* the total amount of water allocated in all mechanisms is the same) and the estimates in column 12 from table 6.<sup>27</sup>

As explained in subsection 2.3, the quota system in Mula allocates the units in sequential rounds of three weeks. *Qc25%* is closest to this system. We now describe how we compute the welfare measures under each mechanism.

### Auctions using Complete Units (*Ac*)

We compute both the revenue and the welfare.

- **Poor farmers:** We compute the revenue using the estimated demand system (*i.e.*  $\hat{\Theta} \equiv (\hat{\gamma}, \hat{\sigma}_\varepsilon, \hat{\zeta})$ ) and the actual purchases made by poor farmers. We use equations 9 (revenue) and 10 (welfare), and the moisture level in the farmers' plots (*i.e.* the moisture resulting from their actual purchase decisions).
- **Wealthy farmers:** We compute the revenue using the estimated demand system (*i.e.*  $\hat{\Theta} \equiv (\hat{\gamma}, \hat{\sigma}_\varepsilon, \hat{\zeta})$ ) and the actual purchases made by wealthy farmers. We use equations 9 (revenue) and 10 (welfare), and moisture level in the farmers' plots (*i.e.* the moisture resulting from their actual purchase decisions). Note that the revenue for wealthy farmers can be greater than the *FBC* average revenue. This is because poor farmers are sometimes liquidity constrained, so wealthy farmers buy more water than the amount required by the *FBC* allocation.

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<sup>27</sup>We obtain similar results simulating the purchase decisions under the auction system and then using the resulting allocation of water to compute the welfare under quotas and *FBC*. Results are available upon request.

## Quotas ( $Q$ )

Revenue and welfare coincide under the quota system because farmers do not choose when to irrigate. We only report one measured that we call “welfare”.

As explained in Section 2, in this paper we focus on the 24 farmers who only grow apricot trees. These farmers bought 633 units of water under the auction system over the sample period. Under the quota system, we allocate the same number of units of water (633 units) in the same week when these units were bought under the auction. We consider three main quota scenarios. In each scenario we allocate units among the farmers as follows:

- **Quotas with random assignment of complete units,  $Qc$ :** every time we observe that a farmer bought a unit of water during the auction on a particular date, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among all farmers.
- **Quotas with non random assignment of complete units,  $QcX\%$ :** every time we observe that a farmer bought a unit of water during the auctions on a particular date, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among the  $X\%$  of farmers who did not receive irrigation the longest, on the same date.<sup>28 29</sup>
- **Quotas with random assignment of fractional units,  $Qf$ :** every time we observe that a farmer bought a unit of water during the auctions on a particular date, all farmers are allocated a fraction of that unit, proportional to their amount of land, on the same date.

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<sup>28</sup>For example, in  $Qc50\%$ , complete units of water are allocated among the 50% of farmers who did not receive irrigation the longest; in  $Qc25\%$ , complete units of water are allocated among the 25% of farmers who did not receive irrigation the longest; and so on.

<sup>29</sup>As indicated in footnote 26, under  $QcX\%$  we need to keep track of when was the last time that each farmer irrigated under the quota system. We do not have this information for the initial weeks in the sample. So, under  $QcX\%$ , we allocate units uniformly at random (proportional to their amount of land) at the beginning of the sample as described in the procedure in footnote 26.



In  $Qc$  and  $QX\%$  units are allocated uniformly at random (proportional to their amount of land) among the corresponding set of farmers. We simulate the allocation  $S = 1,000$  times under  $Qc$  and  $QX\%$ . In Table 7 we report the mean welfare measures across simulations. (In  $Qf$  all farmers are allocated a fraction of the unit proportional to their amount of land, so there is no need to simulate different allocations.)

### First Best using Complete Units ( $FBC$ )

We compute the first best allocation using complete units ( $FBC$ ) allocation as follows. Every time we observe that a farmer bought a unit of water during the auctions on a particular date, the complete unit of water is assigned to the farmer who values the water the most on such date.

## 6.2 Welfare Results

Table 7 displays the the welfare results under auctions, quotas, and the  $FBC$  allocation. We report the mean welfare per farmer, per tree, and per year. The bottom part of the table shows the mean number of units per farmer (during the whole period under analysis) under each mechanism. The total amount of water is the same across all mechanisms (*i.e.* 633 units). The differences in welfare across columns are a consequence of differences in moisture across farmers.

As expected, under the auction system, poor farmers have a lower welfare than wealthy farmers. The quotas system increases poor farmers' revenue and decreases wealthy farmers' revenue. Table 7 shows that the following ranking holds in terms of efficiency:  $FB > Qc25\% > Qc50\% \cong Ac > Qf \cong Qc$ , where a "greater than" inequality indicates greater welfare and where the symbol " $\cong$ " indicates that the welfare is not statistically different. That is, randomly allocating the complete units of water, in proportion to amount of land, results in a decrease in efficiency relative to auctions. In  $Qc50\%$ , complete units of water are allocated among the 50% of farmers who have received less water in the past, in proportion to

Table 7: Welfare Results

|  | Auctions<br>complete<br>units |            | Quotas<br>fractional<br>units |          | Quotas<br>complete<br>units |          |          | First Best<br>complete<br>units |
|--|-------------------------------|------------|-------------------------------|----------|-----------------------------|----------|----------|---------------------------------|
|  | Ac Revenue                    | Ac Welfare | Qf                            | Qc       | Qc75%                       | Qc50%    | Qc25%    | FBc                             |
| <b>Welfare measures:</b> (mean<br>per farmer, per tree, per year)      |                               |            |                               |          |                             |          |          |                                 |
| - All farmers pre-season   | 1192.50                       | 1,200.08   | 1,016.97                      | 1,023.37 | 1,113.57                    | 1,193.42 | 1,265.18 | 1,280.64                        |
| - All farmers on-season  | 1,279.22                      | 1,293.62   | 1,101.66                      | 1,095.29 | 1,209.73                    | 1,307.07 | 1,391.67 | 1,408.54                        |
| - Poor farmers whole season  | 2,102.79                      | 2,124.60   | 2,116.23                      | 2,115.68 | 2,358.44                    | 2,524.46 | 2,596.03 | 2,600.59                        |
| - Wealthy farmers whole season   | 2,832.03                      | 2,860.67   | 2,112.40                      | 2,113.00 | 2,279.53                    | 2,467.90 | 2,709.04 | 2,769.14                        |
| - All farmers whole season   | 2,467.41                      | 2,492.64   | 2,114.31                      | 2,114.34 | 2,318.99                    | 2,496.18 | 2,652.54 | 2,684.86                        |
| <b>Amount of water allocated:</b><br>(mean number of units per farmer) |                               |            |                               |          |                             |          |          |                                 |
| - Poor farmers whole season  | 19.42                         | 19.42      | 25.60                         | 25.62    | 27.07                       | 27.44    | 26.52    | 26.39                           |
| - Wealthy farmers whole season   | 33.33                         | 33.33      | 27.15                         | 27.13    | 25.68                       | 25.31    | 26.23    | 26.36                           |
| - Total units allocated whole season                                   | 633                           | 633        | 633                           | 633      | 633                         | 633      | 633      | 633                             |

Notes: See subsection 6.1 for a discussion about the computation of the welfare measures.

their amount of land. The welfare under  $Qc50\%$  is not statistically different than the welfare under  $Ac$ . (Recall that the welfare under  $Qc$  is simulated  $S$  times.) In  $Qc25\%$ , complete units of water are allocated among the 25% of farmers who have received less water in the past, in proportion to amount of land. The welfare under  $Qc25\%$  is greater than under  $Ac$ . In Mula, the quota allocation mechanism was closer to  $Qc25\%$  than to  $Qc$  because every farmer was assigned a certain amount of water every three weeks (the duration of a round), proportional to their plot's size.

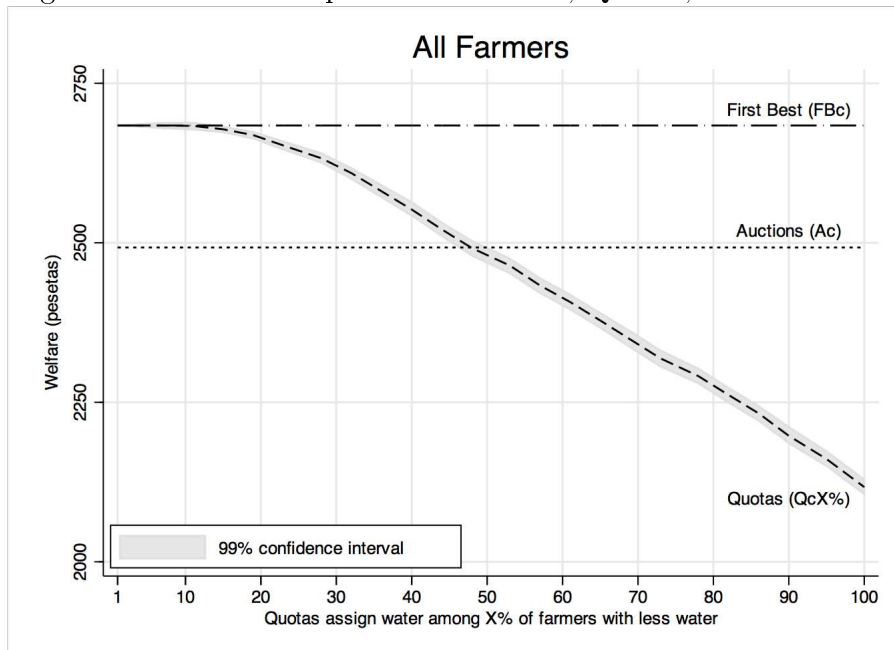
**Auctions, Quotas, and First Best.** Figure 4 shows the welfare comparison among auctions  $Ac$ , the  $FBC$  allocation, and quotas  $QcX\%$  for  $X \in [1, 2, \dots, 100]\%$ . (Note that auctions  $Ac$  and  $FBC$  are constant in  $X$ .) The figure shows the mean welfare per farmer, per tree, and per year. (The welfare measures are the same as in Table 7.) The main difference between  $FBC$  and auctions is that poor farmers do not buy much water during the critical season under auctions  $Ac$ .  $Qc100\%$  is equivalent to quotas with random assignment of complete units,  $Qc$ . Allocating randomly the complete units of water, in proportion to amount of land, results in a decrease in efficiency relative to auctions. This is due to decreasing marginal returns of the apricot production function. Although all farmers receive the same amount of water per tree, the timing of the allocation is important.<sup>30</sup> On the other hand, as  $X$  decreases, the quota system  $QcX\%$  allocates units among the farmers who irrigated less in the past. This is similar to the  $FBC$  allocation, where water is allocated to the farmer who values the water the most. In the limit, as  $X$  decreases enough, the welfare under  $QcX\%$  is similar to the welfare under  $FBC$ .

In practice, varying  $X$  is equivalent to varying the duration of the round. Long round means farmers do not irrigate often, while short rounds means that farmers have to incur the irrigation cost often.

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<sup>30</sup>For example, consider the case of two identical farmers (A and B). Suppose there are four units of water to be allocated in four subsequent weeks (1, 2, 3, and 4). Allocating the first two units during weeks 1 and 2 to farmer A, and the second two units during weeks 3 and 4 to farmer B, results in a lower welfare than allocating the first unit to A, the second unit to B, the third unit to A, and the fourth to B.

Figure 4: Welfare Comparison: Auctions, Quotas, and First Best

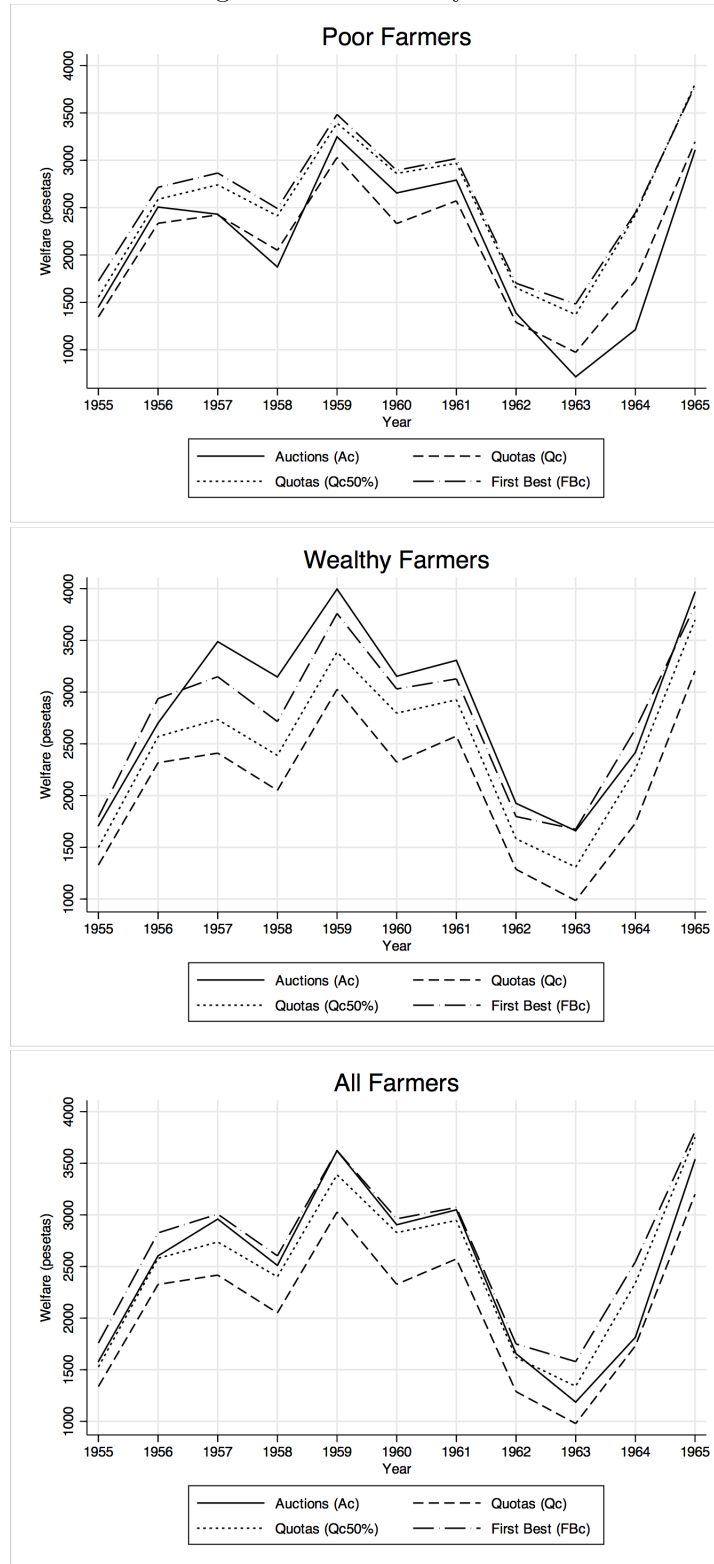


Notes: See subsection 6.1 for a discussion about the computation of the welfare measures.

**Yearly Results.** Figure 5 shows the welfare results by year (1955 to 1965) and by allocation mechanism ( $Ac$ ,  $Qc$ ,  $Qc50\%$ , and  $FBc$ ). There is substantial variation across years, due to variation in rainfall. Revenue is lowest for both poor and wealthy farmers during 1962-63, the driest years in our sample (see Figure 3 in appendix A).

The top two panels in Figure 5 display the welfare disaggregated by poor and wealthy farmers under  $Ac$ ,  $Qc$ ,  $Qc50\%$ , and  $FBc$ . Although the overall performance of  $Ac$  is similar to  $Qc$ , the distribution is different. As expected, wealthy farmers perform better under  $Ac$  than under  $Qc50\%$ . Poor farmers perform better under  $Qc50\%$  than under  $Ac$ . Indeed, during drought years (such as 1958, 1963, and 1964) poor farmers perform better under  $Qc$  than under  $Ac$ . The difference between  $Ac$  and  $FBc$  is the highest in 1963, the year with the highest drought in the sample. The drought increased the price of water relative to the other years in the sample. The negative impact of this drought on poor farmers under  $Ac$  (top left panel) was greater than its positive impact on wealthy farmers (top right panel).

Figure 5: Welfare by Year.



Notes: See subsection 6.1 for a discussion about the computation of the welfare measures.

## 7 Discussion

**Unobserved Heterogeneity.** The differences in production (as a measure of welfare) in Table 7 are due to differences in soil moisture levels (*i.e.* some farmers irrigate more than others) since our specification assumes that all farmers are equally productive, up to an idiosyncratic productivity shock. An alternative explanation would be that differences in production are due to unobserved differences in productivity. For example, it could be that wealthy farmers used additional productive inputs (*e.g.* fertilizers, hired labor, manure, *etc.*) in greater quantities than did poor farmers. Thus, the argument continues, poor farmers' production would be lower than wealthy farmers' production due to both differences in soil moisture levels and greater use of these additional productive inputs.

We cannot rule out this argument because (1) our econometric specification does not allow for persistent differences in productivity among farmers, and (2) we have no data about the relative use of these additional productive inputs. However, we believe this would not affect our counterfactual results from Table 7 for two reasons. First, if wealthy farmers used additional productive inputs in greater quantities than did poor farmers, the transition from auctions to quotas would increase the production of poor farmers more than we predicted in the counterfactual from Table 7. This is because, under quotas, farmers do not have to pay for the water (only the maintenance costs of the channel which are substantially lower than the price of water in the auction), leaving them extra cash to buy additional productive inputs (unless one argues that poor farmers had no access to these additional productive inputs due to, for example, a knowledge advantage of the wealthy farmers).

Second, the estimated scale parameter,  $\hat{\sigma}_\varepsilon$ , in Table 6 is close to one (columns 4-6 and 10-12). This indicates that allowing the distribution of idiosyncratic productivity shocks,  $\varepsilon_{ijt}$ , to have a different variance, does not affect the estimates significantly. We interpret this as indirect evidence that farmers' heterogeneity is not large. Note that this is an informal argument because, as noted in point (1) above, our econometric specification does not allow for persistent differences in productivity among farmers.

**Strategic Supply.** The president of the *Heredamiento de Aguas* made the decision whether to run the auction or not. There is no evidence that running the auction, or not, was a strategic decision. If there was enough water in the dam, the auction was held. However, the president could stop the auction at any time, and indeed used to do just that if the price fell considerably, usually to less than 1 *peseta*. This uncommon situation happened only after an extraordinary rainy season. The president's decision about when and whether to sell water was profit-maximizing, not necessary welfare-maximizing.

**Strategic Size and Sunk Cost.** The results obtained when comparing revenue from quotas and auctions suggest that the choice of the unit size in the auction (*i.e.* three hours of irrigation) was not innocuous. In particular, the fact that in some years poor farmers under the quota system produced higher revenue than wealthy farmers under the auction system suggests that the size of the units sold at the auction might be too large. The size of the units sold at auction has not changed since the middle ages. This could be due to institutional persistence or due to technical reasons. For example, three hours could be the size that maximizes revenue. So it could be the case that 3 hours maximizes profits, but not welfare.

As shown in Donna and Espín-Sánchez (2015), there is a sunk cost to the first unit of water allocated to a plot because the dry channel absorbs some water. Subsequent units associated with the same channel flow through a wet channel, thus, the loss is negligible. In the auction system, subsequent units are allocated to different farmers, depending on who has won each unit. The optimal size of the unit (*i.e.* the size of the unit that maximizes welfare) would be determined by a trade-off between the sunk cost incurred every time a farmer irrigates, due to the loss of water flowing through a dry channel, and the diminishing return of water. In the quota system, units are allocated to each farmer in geographical order (*i.e.* every unit is allocated to a neighbor farmer down the channel with respect to the previous farmer).<sup>31</sup>

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<sup>31</sup>In the neighboring city of Lorca, auctions are carried out independently for farmers with lands in each

**Optimal Crop Mix.** Our analysis only considers the case in which farmers grow apricot trees. Since different agricultural products have different irrigation needs in different seasons, the optimal crop mix involves diversifying among several agricultural products with different irrigation needs. For example, oranges are harvested in winter, and their need for water peaks in December. Apricots are harvested in summer, and their need for water peaks in May-June. Hence, a crop mix with apricot and orange trees would outperform one with just apricot trees. We observe this optimal mix in the data. Many farmers have orange trees and either apricot, peach, or lemon trees, all three of which are harvested during summer. In this paper we focus on the set of farmers who only grow apricot trees because they have the same production function. This allows us to account for unobserved heterogeneity without modeling it, as discussed above in this section.

**Trees.** Quotas are desirable during a drought because they allocate a certain amount of water periodically to each farmer. Quotas also function as insurance for farmers, who have less uncertainty when carrying out risky investments, such as trees. A tree takes several years to be fully productive, but will die if it does not get enough water in any given year. On the other hand, vegetables grow more quickly than trees, and can be harvested within a year of planting. Hence, a farmer with a secure supply of water is more likely to plant trees and receive a higher expected profit from them.

**Liquidity Constraints vs Risk Aversion.** One of the concerns in identifying liquidity constraints (LC) is that some empirical implications of markets where agents face LC are similar to those of markets where agents are risk averse. In particular, poor farmers buying water before the critical season (*i.e.* before the uncertainty about the rain is realized) is consistent with both LC and risk aversion. We now use the response of poor farmers to their purchase timing to investigate this concern.

The main difference in farmers' behavior under LC and risk aversion occurs during the 

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sub-channel. This way, the water has to travel shorter distances and the amount of water lost is smaller.



summer, when prices are high. If poor farmers are liquidity constrained, then they will not be able to buy water when the price is high, even if the moisture level in their plots is low. On the other hand, if farmers are unconstrained, but risk averse, they will have the same demand for water as wealthy farmers during the summer, after the weather uncertainty is realized in Spring before the critical season, conditional on soil moisture levels.<sup>32</sup> Column 4 in Table 4 shows that holding the moisture level fixed, poor farmers buy less water than wealthy farmers. Following the results in this table, along with the opinions presented in above, we conclude that poor farmers were liquidity constrained.<sup>33</sup>

## 8 Concluding Remarks

In this paper we empirically investigate the welfare effect of a historical institutional change from auctions to quotas. A market institution, an auction, was active for more than 700 years in the southern Spanish town of Mula. The system allocated water to farmers for agricultural purposes. In 1966, a fixed quotas system replaced the auctions. Under the quota system, farmers who owned a plot of fertile land were entitled to a fixed amount of water, proportional to the size of their plot, for irrigation.

In the absence of frictions, a water auction is efficient because it allocates water according to the valuation of the bidders. When frictions are present, however, markets may not be efficient. Frictions arose in Mula because farmers had to pay cash for water won in the auction, but did not always have enough cash during the critical season, when they needed water the most. When farmers are liquidity constrained, the efficiency of auctions relative to quotas is ambiguous. It is then an empirical question which institution is more efficient.

We show that, as some historians have suggested, some farmers were liquidity constrained

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<sup>32</sup>The same argument rules out the possibility that the results are driven by poor farmers being more impatient than wealthy farmers.

<sup>33</sup>In this paper we abstract from differences in prices within the week (*i.e.* Monday to Friday, and Day to Night). However, differences in prices within the week can also be used to assess the importance of LC. As shown in Donna and Espín-Sánchez (2015) prices are higher for night-time irrigation and higher earlier in the week (prices on Mondays are higher than on Fridays). Although not reported here, we find that that poor farmers are more likely to buy water during nights and later in the week.

in Mula. Poor farmers bought less water than wealthy farmers during the critical season and obtained lower revenue per tree as a consequence. To compute welfare under auctions and quotas, we first estimate the demand system. To estimate demand, it is necessary to account for three features of the empirical setting: intertemporal substitution effect, liquidity constraints, and weather seasonality. Ignoring the presence of liquidity constraints (LC) biases estimated (inverse) demand and demand elasticity downwards.

We use the estimated demand system to compare welfare under auctions, quotas, and the first best allocation. We conclude that a necessary condition for quotas to increase efficiency relative to the auction in our setting, is that units of water are allocated according to farmers' valuations. In Mula, the institutional change improved efficiency (the quotas generated greater welfare than the market). Hence, the end of the water market in Mula was a "settled problem of irrigation."

The contributions of this paper are twofold. First, from a historical perspective, we provide empirical evidence of a source of inefficiency in water markets. We also provide empirical support for the institutional change proposed in Espín-Sánchez (2015). Second, we propose a dynamic model that includes storability, seasonality, and LC. We discuss the relationship between storability and LC, and show that ignoring the presence of LC biases the estimated demand downwards.

The empirical results in this paper apply only to our empirical setting. One should not conclude that all water markets are inefficient. We have presented an empirical framework with the main ingredients found in other water markets: seasonal demand, storability, and LC. Accounting for the specifics of other empirical settings, our framework can be used to assess the efficiency of water markets in those settings.

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