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Growing crops in arid, drought prone environments: adaptation and mitigation

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Abstract: Drought poses significant risks to society, in particular irrigated crop production which accounts for a large share of global freshwater use. Given its key role for the production of food, feed and fiber crops, there exists a need for policy measures to prevent and mitigate the impacts of drought on irrigated agriculture. This paper proposes that the design of drought policy should take into account actual farmer behavior in response to water scarcity. To this end, we offer a detailed analysis of land allocation and crop choice decisions over time in an irrigation district located in the dry plains of Northern Mexico. We find that farmers systematically change their crop mix in response to water availability. In particular, in times of drought irrigation water flows to higher-yield and higher-price crops (which also require more intense irrigation) to the detriment of less water-demanding (but lower value) crops. Farmers use water with the goal of earning a living – economizing on water per se has no relevance in that context. Policies that do not explicitly recognize this may result ineffective or produce inefficient or unfair outcomes.

Keywords: agriculture; irrigation; crop choice; land allocation; drought

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1. Introduction

How should crop producers adapt to water scarcity? In particular, how should they mitigate the impacts of periods of exceptionally low water availability, i.e. drought? This paper addresses this normative issue based on the following positive premise: the design of effective, efficient and fair water and drought policies requires an understanding of how crop producers actually deal with water scarcity and drought.

To this end, the paper proposes a general representation of irrigated crop production that focusses on land use, crop choice and irrigation intensity (i.e. the ratio of irrigation water to land). Second, the paper offers an empirical application of this framework for a particular crop production system, a large irrigation district located in the dry northern plains of Mexico, over a two-decade period of time. Results show that producers have developed an array of responses to deal with water scarcity and drought. Notably, in the face of drought producers do not strive to economize on water, rather they seek to limit the loss of income.

The extensive literature on the economic value of water in agriculture, for example [1-3] is tangentially relevant to the work presented here, whose conceptual and methodological outlook is simple and descriptive, yet innovative and easily reproducible. The rest of the paper is organized as follows. Section 2 defines the variables to be analyzed, introduces the constituent parts of the analysis and offers background information on the irrigation district under study. Section 3 presents the results: characteristics of the water environment faced by irrigators; land allocation and crop choice decisions through time and with respect to water availability; outcomes obtained by farmers, both agronomical and economic. Section 4 proposes an interpretation of the results obtained, suggests implications for water and drought policy and concludes.

2. Materials and Methods

At the beginning of agricultural season t, producers decide how much land to plant (Lt) and which crops to grow, given the expected volume of water available for irrigation (Wt):

$$L_t(W_t) = \sum_{i=1}^{n} l_{it} \le \Lambda \,, \tag{1}$$

where l_{it} represents the surface of land allocated to crop i (i=1,…,n) and Λ, the surface of irrigable land. The land allocation/crop selection decision results at the end of the season in a net revenue Rt:

$$R_t = \sum_{i=1}^{n} (p_{it} \cdot y_{it} - c_{it}) \cdot l_{it} \,, \tag{2}$$

where p_{it} represents crop price (per ton of crop), y_{it}, yield (tons of crop per hectare) and c_{it}, production costs (per hectare).

We examine the relationships and trends over time for the quantities defined in Equations (1) and (2) in three steps. First, we describe the water environment faced by producers in terms of variability and scarcity. Second, we analyze the land allocation/crop choice decision in relation to water availability. Third, we assess the system's robustness and resiliency based on the agronomical and financial outcomes obtained, e.g. yields and revenues per unit of land or water. We apply the procedure to a particular crop production system, Irrigation District 017 (Distrito de Riego 017 Comarca Lagunera) in Northern Mexico (Figure 1), over the 1998-2018 period.

Figure 1. Irrigation District 017 and surrounding region. **Key**: (1) Lázaro Cárdenas dam/reservoir (Upper Nazas River Basin); (2) Nazas River; (3) Francisco Zarco dam/reservoir (Middle Nazas River Basin); (4) Urban area: cities of Torreón, Coahuila (right bank), Lerdo and Gómez Palacio, Durango (left bank); (5) Irrigation District 017 (Lower Nazas River Basin). **Source**: Authors.

The District's 72 thousand hectares straddle the states of Coahuila and Durango, in the lower part of the endorheic (closed) Nazas River Basin. Local precipitation, at about

200mm per year on average, does not provide for rainfed farming. For irrigation purposes the District's producers depend entirely on run-off generated in the more humid upper basin and channeled through the Nazas River. The Lázaro Cárdenas dam/reservoir, with a capacity of 2,873 million cubic meters (Mm3) provides almost all of this water, which flows downslope through the river for about 220 kilometers (km) to the District. On its way the river meets the relatively small Francisco Zarco dam/reservoir which mostly functions as a regulating buffer.

Located in the vicinity of an urban area of 1.2 million inhabitants, formed by the contiguous municipalities of Torreón, Lerdo and Gómez Palacio, the District plays a key role in the local and regional economy. The region also hosts a large livestock industry – more than nine hundred thousand heads of dairy and beef cattle as of 2020 – and is home to one of the biggest dairy and meat products conglomerates in Latin America, *Grupo Lala*.

3. Results

3.1. The water environment

The Upper Nazas River Basin – the source of water for Irrigation District 017 - consists of more than 18 thousand km2 of rugged, mountainous terrain with peaks of up to 3,300 meters above sea level (masl). Precipitation varies from year to year as well as spatially within the area (yearly averages range from 350 mm to 900 mm). Historical data from 17 weather stations reveal numerous episodes of severe droughts in the region over the past century – of particular relevance here, from the late 1990's to the early 2000's and again in the early 2010's [4].

Inter-annual variability in precipitation modulates the run-off captured by the Lázaro Cárdenas dam/reservoir, located within the upper basin at just under 1,600 masl. Over the period 1998-2018, beginning-of-year storage in the reservoir has averaged 1,726,312 thousand cubic meters (K m3). Yearly figures have fluctuated widely around that average with periods of relative scarcity up to 2004 and again in 2013, as well as relative abundance for the three consecutive years 2009-2011 (Figure 2).

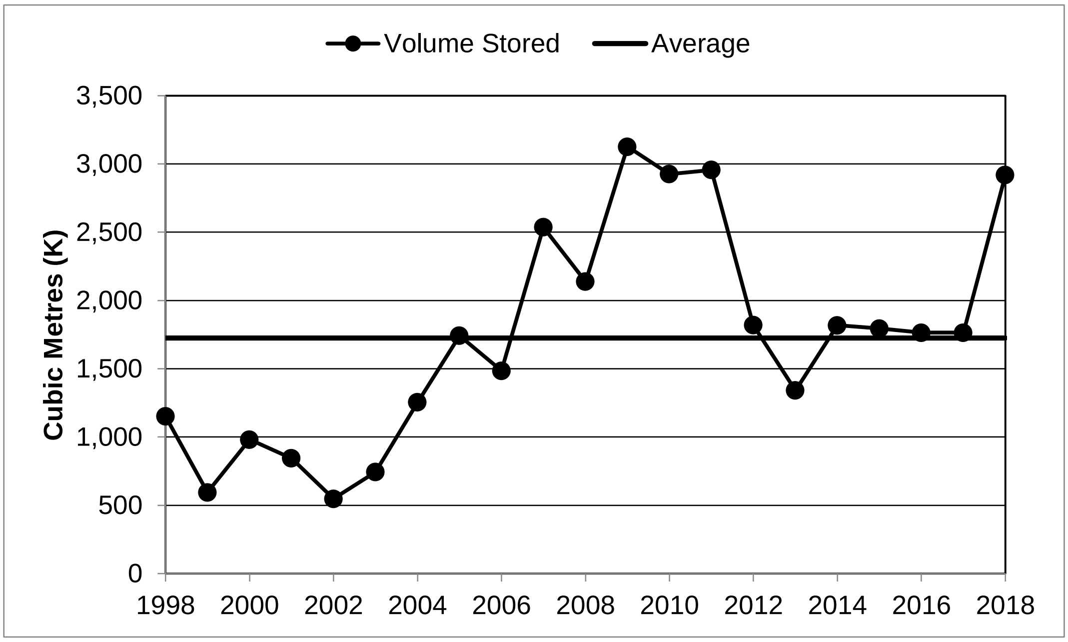

Figure 2. Water stored at beginning of year, Lázaro Cárdenas dam/reservoir, thousand cubic meters (Km3), 1998-2018. **Source**: Authors with data from [5].

Water distributed and land irrigated in the District, W_t and L_t respectively as defined in (1), have varied in close relation with volumes available in the reservoir (Figure 3). Water has proved scarce relative to land: the District has tended to operate below its 72,000 hectares capacity, except during the 2009-2011 period of relatively abundant water. In 2002 at the peak of drought, only 12,378 hectares received irrigation.

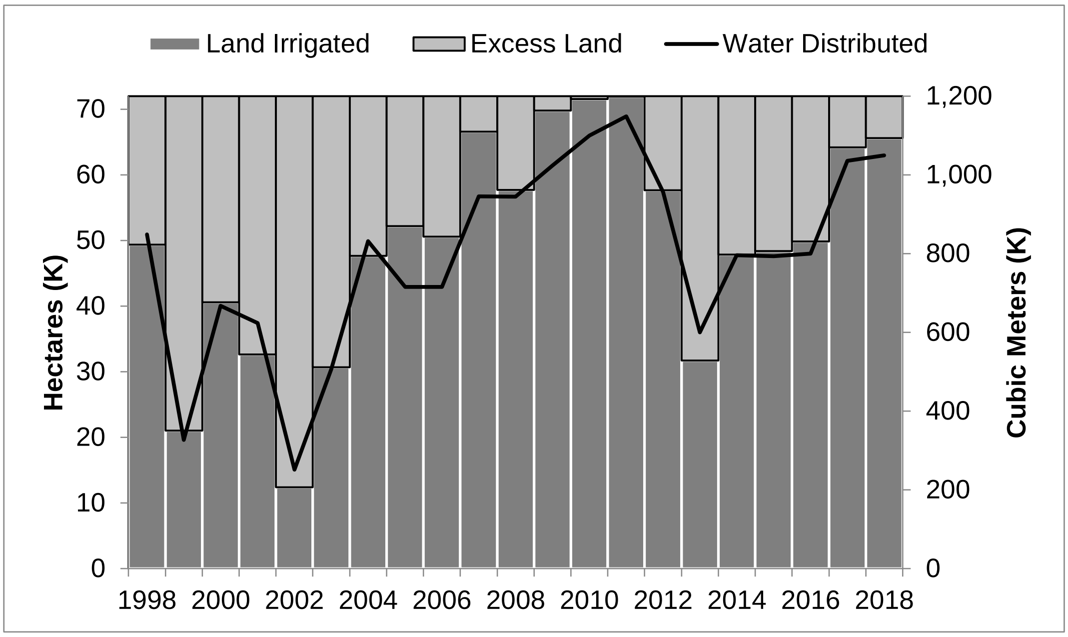

Figure 3. Water distributed and land irrigated per year, Irrigation District 017, 1998-2018.. **Source**: Authors with data from [6].

The tight relationship between Wt and Lt (correlation coefficient of 0.97) suggests the District's producers follow a simple rule to deal with water scarcity and variability: in every year, adjust the surface of irrigated land in proportion to the volume of water available. As the results in the following section show, within that minimal, reflexive framework irrigators in fact deploy distinct adaptation and mitigation actions.

3.2. Land allocation and crop choice

The District produces a variety of feed, fiber and food crops for local, national and export markets. The more than two dozen distinct crops on the District's production records for the 1998-2018 period fall into two main categories: seasonal and perennial.

Cotton and two feed crops (corn green forage and sorghum) have dominated land use in the District. These three seasonal crops have accounted for almost 70% of total cumulative land use during the 1998-2018 period. Two perennial crops (alfalfa grown for feed and walnut) have cumulated a further 19% of land use. A handful of seasonal fruits and vegetables (watermelon, cantaloupe, green chili, red tomatoes and beans) have accounted for half of the remaining 11% of cumulative land use in the District.

Year-to-year land use has differed widely for the two crop categories (Figure 4). The surface dedicated to perennial crops has tended to grow steadily over time, from 8.5 thousand hectares (K ha) in 1998 to 12.3K ha in 2018, albeit with fluctuations around that trend. In contrast, land for seasonal crops has varied widely and in close relationship with water available for irrigation (correlation coefficient of 0.96). The simple rule described earlier evidently includes a clause whereby seasonal crops bear the brunt of the adjustment of land with respect to water. Note that for both seasonal and perennial crops, the minimum in surface cultivated occurred in 2002, the year of maximum water scarcity.

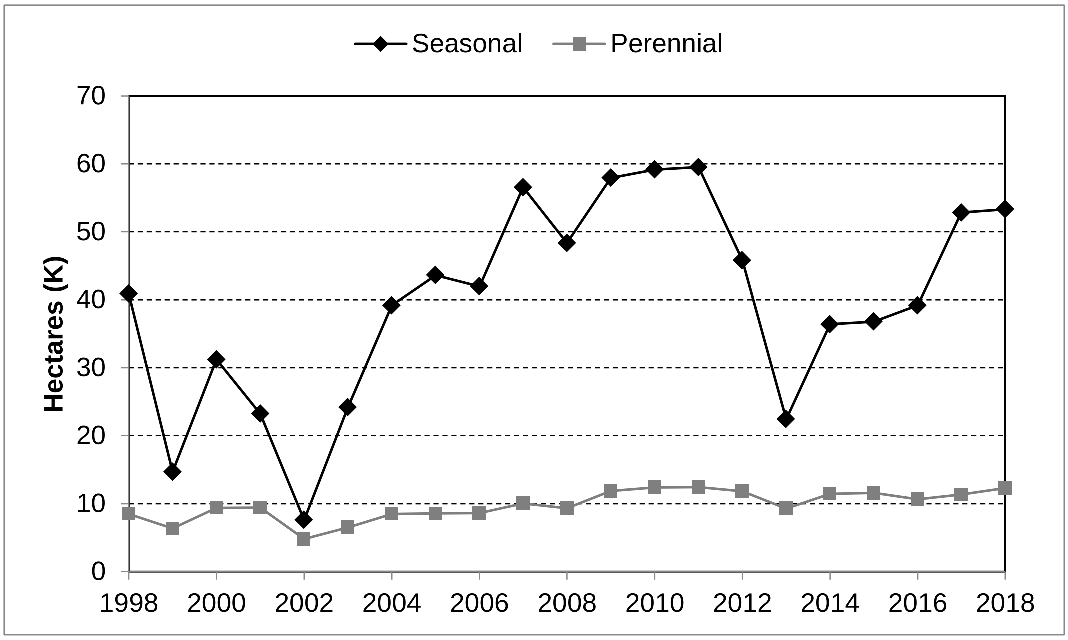

Figure 4. Seasonal and perennial crops surfaces, Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

Changes in land allocation affect irrigation intensity, i.e. the ratio of water applied to land, here expressed as depth of water in centimeters, per hectare of land. The perennial crops grown in the district have higher water requirements than the seasonal crops. Consequently the larger the percentage of land allocated to perennial crops, the higher irrigation intensity (Figure 5). Irrigation intensity reached a maximum of 203.3 cm/ha in 2002, the peak drought year, well above the average of 163.7 cm/ha registered during the 1998-2018 period.

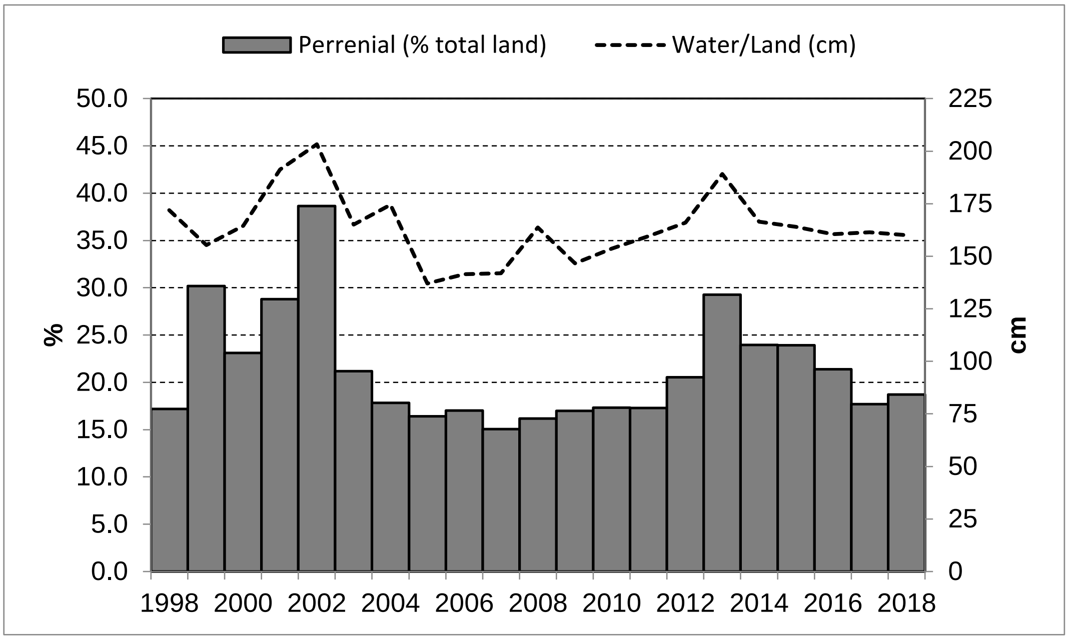

Figure 5. Irrigation intensity, Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

Summing up, crop growers in Irrigation District 017 follow a two-level rule to manage their irrigation water. First, water availability determines the total surface of land cultivated, more or less in a mechanical fashion. Second, the lower (higher) the amount of water available, the higher (lower) the proportion of land allocated to perennial crops i.e. seasonal crops bear most of the adjustment of land to water. In years of drought, the rule results in a more intense use of water per unit of cultivated land as perennials have greater water requirements than seasonal crops.

The logic behind the rule is two-fold. First, perennials obviously constitute long-term assets that might be worth protecting in dry years. Second and more importantly, the perennial crops grown in the District tend to produce higher yields (i.e. tons of crops per hectare) than seasonal crops. In fact, the distribution of yield values for perennial crops dominates absolutely that for seasonal crops (Figure 6).

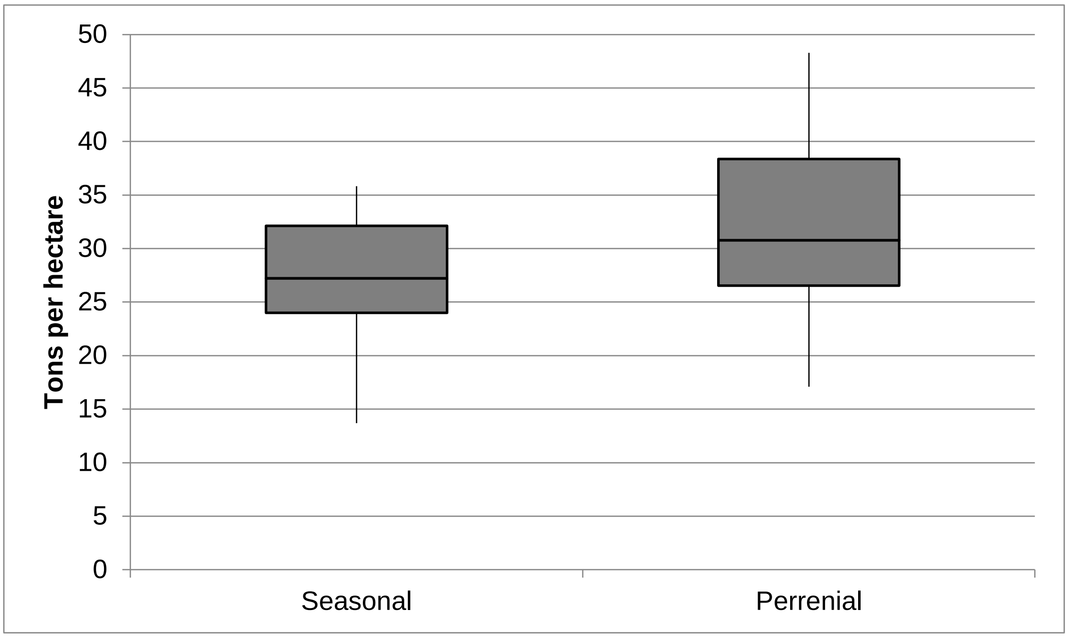

Figure 6. Yields by crop type, box diagram, Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

Perennial crops also tend to command higher prices per ton of crop (Figure 7). Consequently, perennials tend to generate higher revenues per unit of land in comparison to seasonal crops and the growers’ rule for managing their water allows them to sensibly mitigate the impact of drought on their revenues.

Note that the previous is driven by two facts: alfalfa produces more feed per hectare (on average 56 tons) than either corn or sorghum (on average 44 and 48 tons respectively) and walnut is by far the most valuable of all district crops. Over the 1998-2018 period walnut growers obtained on average MXP42,310 per ton for their produce, while average prices for alfalfa, corn and sorghum, reached MXP701, MXP538 and MXP509, respectively.

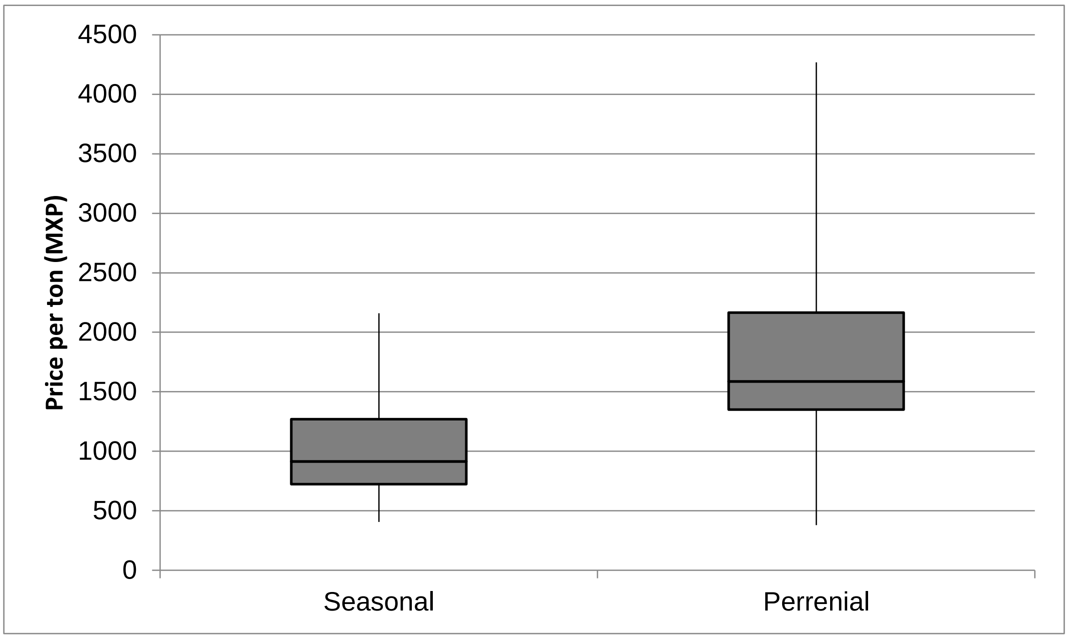

Figure 7. Price per ton by crop type, box diagram, Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

3.3. Outcomes

3.3.1. Agronomical outcomes: crop failures and yields

Of the cumulative 1,039,987 hectares cultivated in the District from 1998 to 2018, 1,947 (less than a fifth of one percent) failed to produce a harvest. No seasonal crop has suffered failure and all failure events have involved only two perennial crops. The last crop failure event occurred in 2011 when 20 hectares of fig trees did not yield fruit; all previous events affected walnut orchards (Figure 8). The data suggest walnut growers have managed to gradually solve this problem – from 2005 on, walnut orchards have produced on 100% of their land area.

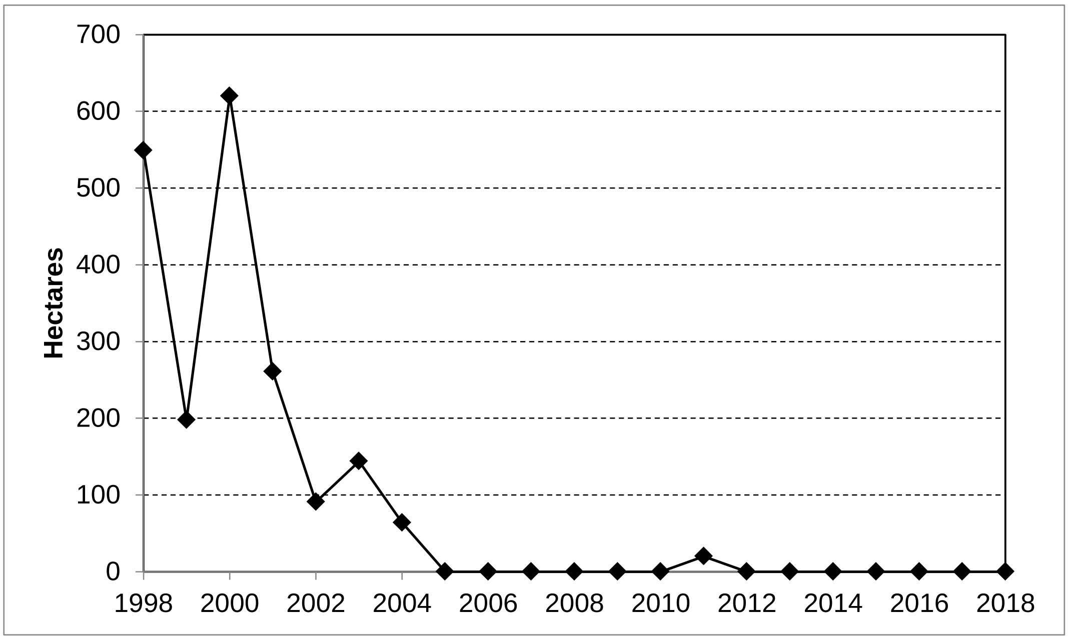

Figure 8. Crop failure (hectares), Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

Yields in the district have varied from year to year but the data do not reveal any discernible trends. Table 1 presents the basic descriptive statistics for the five main crops. Corn green fodder lends itself particularly well to international comparisons, as the harvest consists of the whole plant and is usually weighed as fresh matter. Fresh matter yields of corn green fodder range from 10 to 50 t/ha globally [7]; the District has consistently performed in the upper part of that band (Figure 9).

Table 1. Yields (tons per hectare), main crops, Irrigation District 017, 1998-2018.

	Cotton	Corn	Sorghum	Alfalfa	Walnut
Minimun	2.41	35.40	31.40	28.68	0.84
Median	4.92	44.90	48.23	54.90	1.78
Mean	4.59	43.77	48.04	55.62	1.71
Maximum	5.52	51.20	57.79	76.33	2.13

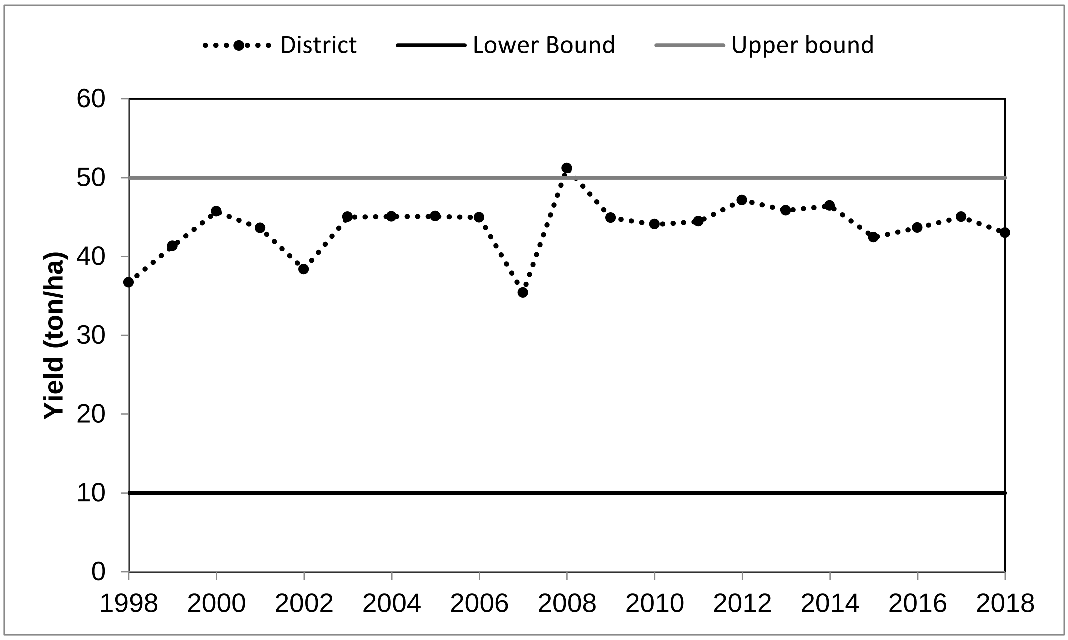

Figure 9. Corn green fodder yield, Irrigation District 017 and global upper and lower bounds, 1998-2018. **Source**: Authors with data from [6].

3.3.2. Economic outcomes: revenue per hectare, revenue per unit of water

Revenues obtained by irrigators result from a combination of decisions (e.g. land allocation/crop selection) taken in light of exogenous factors (e.g. crop prices and water availability). Gross revenue per hectare in the District has fluctuated around an upward trend (Figure 10). In real terms (i.e. taking into account the general inflation rate in Mexico), gross revenue per hectare has increased at an average rate of 3.3% per year over the 1998-2018 period. In the case of gross revenue per cubic meter of irrigation water (Figure 11), growth has proved more robust, with an average rate of increase of 4.0% per year.

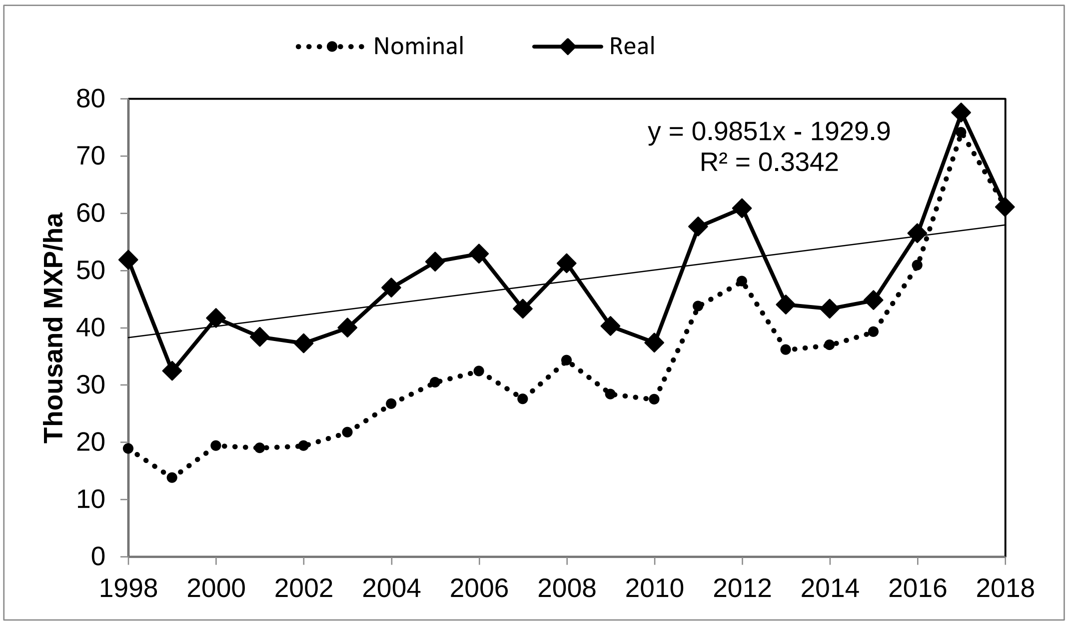

Figure 10. Revenue per hectare, Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

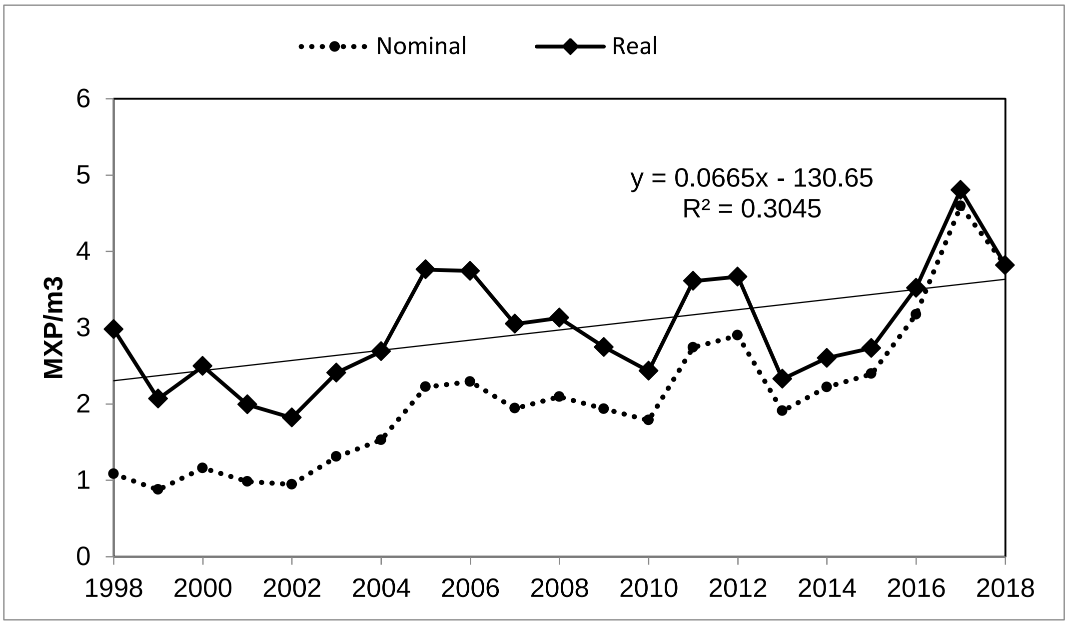

Figure 11. Revenue per unit of water (m3), Irrigation District 017, 1998-2018. **Source**: Authors with data from [6].

3.3.3. Regional outcomes: feed output and the dairy and meat industry

The District forms part of a larger agro-industrial regional system and supplies feed (corn, sorghum and alfalfa) for the neighboring dairy and beef cattle industry. The total quantity of feed produced yearly depends on water availability and the previously described rule irrigators follow to manage water scarcity and drought. During 1998-2018, the corn green feed (sorghum) harvest averaged 531,424 (442,050) tons but in 2002 at the height of drought, amounted to only 101,718 (104,517) tons. Data available on total milk production in the region [8] suggest the dairy industry is largely immune to the variability in the Districts' feed output (Figure 12). Data on herds show that the number of heads for dairy (beef) cattle has grown from 427,874 (133,402) in 2011 to 506,217 (410,806) in 2020 – an 18% (208%) increase [9].

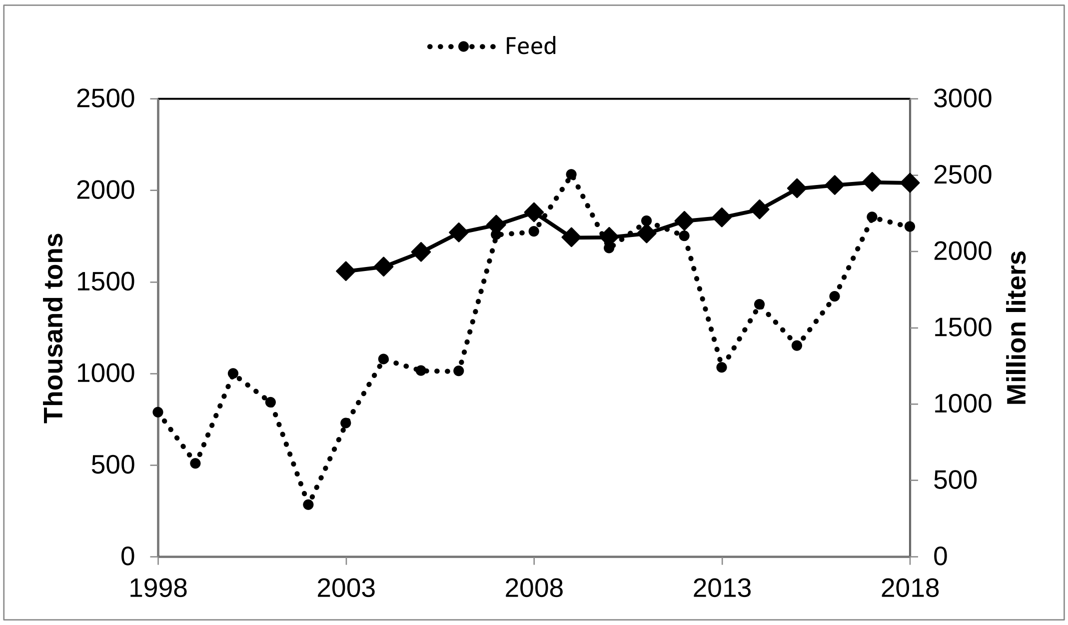

Figure 12. Feed production, Irrigation District 017, 1998-2018 and regional milk production (million liters), 2003-2018. **Source**: Authors with data from [6] and [8].

4. Discussion and conclusions

The results of the previous section describe a resilient, high-functioning system adapted to the challenging water environment in which it operates and capable of mitigating the impacts of climate variability, in particular drought. The District's recent history provides clues about the causes that underlie its performance.

Until the mid-90s the District exploited an area of up to 105,000 hectares (45% larger than the 72,000 reported in this paper) thanks to the extensive use of underground water [10]. The federal water authority at that time introduced a series of reforms for the District - in Mexico, water is national property and the federal government regulates its use across sectors through a system of water rights. Most importantly District irrigators lost access to underground water. This led inevitably to a downsizing of operations however irrigators also gained the right to trade their water allocations among themselves.

Studies about that water market have raised questions about its fairness [11]. Results presented here suggest it has contributed to efficiency, by allowing the smooth flow of water available to its most economic use from year to year according to circumstances. The District is neither a corporation nor a soviet - rather, it is a collection of several thousand independent farmers. Patterns of land allocation and water use such as described in Figure 4 would be impossible to achieve without a functional water market.

This paper carries implications for water and drought policy. Farmers grow crops for one purpose: to make a living. They will not economize on water unless such economizing contributes to said purpose. As an analogy, consider the issue of mechanization for harvesting crops. A farmer will acquire the equipment on the basis of costs and benefits, not for the sake of reducing labor-time per unit of output, per se. Water and drought policy measures (whether preventive or emergency) should explicitly take into account farmer (i.e. human) behavior, otherwise the results could turn out ineffective, inefficient and/or unfair. For example, in this case irrigators do not shift to relatively low water requirements crops in times of acute water scarcity. Mandating such practice (which could appear reasonable from a strict environmental viewpoint) would cause them harm and impair future productivity.

Drought poses many difficult challenges for all economic sectors and society at large. Studies like the one presented here could easily be replicated in different locations to build knowledge on how farmers deal with drought according to their circumstances, from the characteristics of the water environment they face to the institutional arrangements that facilitate (or impede) their decision-making. Such knowledge, beyond informing policy design at a local level, could lead to the identification of patterns of deeper significance.

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