The Effects of Water Markets: Evidence from the Rio Grande[1]

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Abstract

The Rio Grande water market is one of the oldest water markets in the United States. We present the first difference-in-difference analysis of the impact of water markets on production. We compare, from 1954 to 2012, the change in the crop composition in counties in the Rio Grande water market with neighboring control counties before and after the water market was established in 1971. We provide evidence that water markets facilitate a shift from low- to high-value crops, or, in terms of our empirical proxies, from less productive crops that generate on average less dollars per unit of water to the ones that are more productive. We find that such reallocations are especially prevalent in times of drought. Our findings support water markets as a tool to manage water more effectively, which is one of the main challenges of an increasingly water-strapped world.

Population growth, economic development, and climate change make water increasingly scarce in many regions of the world. In spite of many reports in the media, water is a renewable resource and the world is not running out of water. There is, however, a need to improve how water is managed, how it is distributed among its competing uses, and also how efficiently it is used. This need is all the more pressing as there is little appetite to build (environmentally) costly dams, reservoirs, canals, or wells.[2] It is against this background that we study water markets empirically. Economists have advocated the use of markets to address environmental challenges for quite some time. Markets should have potential especially for allocating water more efficiently, since water is often in public hands and priced according to political consensus.[3] The price signals that

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[2] UN (2012) calls for better water management. Zetland (2011) and Griffin (2016) describe the changing response to water scarcity from increasing water supply to demand management. Debaere and Kurzendoerfer (2015) documents how the changing composition of the U.S. economy accounts for 35 to 50% of its water productivity gains since 1950. Debaere (2014) illustrates how water resources affect the international pattern of production and trade.

[3] Early references are Howitt et al. (1984) and Howe et al. (1986). Colby et al. (1987) and Easter et al. (1998) are influential publications covering many aspects of water markets with multiple case studies.

markets send could trigger a more flexible and decentralized response to droughts and changing environmental and economic conditions, which could make economies more resilient. [4]

Water markets are increasingly used and promoted in the United States, Australia, Chile, and elsewhere. They are cap-and-trade systems in which water rights are bought, sold, or leased independent of the land title. [5] [6] Economic theory has it that water trading brings about a more efficient water allocation. Those who can use water most productively *at the margin* are eager buyers of water, whereas *marginally* less-productive users are willing sellers. We investigate a common but untested prediction about the shift in production that water markets induce. With an explicit price of water and a cap on overall water use, water markets should move production from low- to high-value activities, which is short for saying away from activities that *on average* use less to ones that use more (non-water) factors of production per unit of water. To study this prediction, we focus on agricultural production in the Rio Grande water market, which is one of the U.S.' oldest markets.[7] In terms of our empirical proxies, our exercise amounts to checking whether water markets increase the share of crops that are on average most productive in terms of dollars in sales per units of water compared to those that are less productive.[8]

Agriculture is under pressure to feed the world's ever-growing population. It is an open question how agriculture, the world's heaviest user of water, adapts to a changing climate.[9] It is clear that ever more prevalent irrigation will play an important role in agriculture's adaptation.[10] It is here that water markets could play a key role. In the absence of an overall cap on water use and a realistic price of water, the trajectory of water use in agriculture is all too familiar. As has been observed in the Great Plains above the Ogallala aquifer, irrigation is often associated with agricultural expansion, a gradual shift toward more (not less) water-intensive crops, and depleting (ground) water resources. [11] The reason for this unfortunate trajectory is well understood. Water is the ultimate open-access resource that is often available for free, which invites overuse. Water markets, on the other hand, hinge on the private assignment of property rights, and they are an answer to the tragedy of the commons. To see whether water markets

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[4] Dinar et al. (2015) survey existing water-pricing policies worldwide. Olmstead (2010) emphasizes the role of price adjustments in quelling existing concerns of the limits-to-growth debate of the 1970s.

[5] For surveys and broad-based assessments of water markets, see Chong and Sunding (2006), Grafton et al. (2011), Grafton et al. (2012), and Debaere et al. (2014). Garrick et al. (2013) discusses the evolution of water markets.

[6] This distinguishes water markets from groundwater ranching (buying land with associated groundwater resources) or internal water transfers within a district; see Chang and Griffin (1992).

[7] Ghimire and Griffin (2014) study the role of water districts on transfers between agriculture and cities.

[8] We prefer to use the common terminology of low- versus high-value activities, and its reference to its use of more or less (non-water) production factors per unit of water, and its higher or lower output to water rate, rather than refer to more or less water intensive activities. 'Water intensity' is often defined in the literature in purely physical terms such as water per kilo or water per hectare, almost devoid of economic value creation. Crops can require similar amounts of water per kilo or hectare, but the high value crops will be those that in addition use more capital, labor, etc.

[9] Hornbeck and Keskin (2014), Hornbeck (2012), Deschênes and Greenstone (2007), Conan (1911), Libecap (2011), Ostrom (2011).

[10] According to the FAO Aquastat, 13% of arable land was irrigated in 1961, and 23% in 2010.

[11] Hornbeck and Keskin (2014) and Sekhri (2011).

are effective, it is therefore critical to understand whether and how water markets alter the crop composition.[12] We study the Rio Grande market in Texas that came online in the early 1970s after a lengthy adjudication process and a lawsuit to prevent overuse. Between 1954 and 2012, we investigate with county-level data whether water markets change the composition of crops that are grown in water market counties compared to neighboring control counties. To our knowledge, ours is the first difference-in-difference analysis to investigate the actual impact of water markets on production.

Our difference-in-difference approach differs markedly from the existing literature. Linear programming methods and simulations are common to assess the potential gains from water trading.[13] While such analyses are insightful, to some extent, they assume the optimal outcome. They do not tell us whether the optimal crop allocation actually materializes once a water market is in place. Alternative approaches rely on price and volume data from actual water transactions, see Chang and Griffin, 1992, or on survey data of past transactions, as in Hearne and Easter (1999). We sidestep some of the challenges of such studies that relate to the quality and availability of price and quantity data, and the complexity of water-market transactions. Instead, we investigate the changing production patterns due to a water market.[14] Note that there is also a small experimental literature on water markets that seeks to understand their operation and impact with well-designed experiments in the lab.[15]

Any student of water markets quickly realizes that water-market transactions are relatively complex. There are many institutional and practical hurdles to make one doubt their effectiveness.[16] There is a theoretical literature that studies, often with simulations, many potential complications to their proper functioning. It has been studied how the gains from water trading interact with search or intermediation costs, drainage, and environmental pollution; researchers have looked at how water markets are impacted by uncertainty and asymmetric information, different types of water rights or technologies, and orderings of crop plantings; it has been investigated how water markets are affected by interactions between ground and surface water, or by deviations from perfect competition.[17] This theoretical literature and its complexity opens the door for an almost limitless number of possible circumstances and water-market outcomes. It is against the background of this literature that our paper is to be read.

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[12] Hardin (1968).

[13] See Easter, et al. (1998), Howitt and Vaux (1984), Dinar and Letey (1991), Weinberg et al. (1993), and Rosen and Sexton (1993) for a few examples.

[14] Data availability for water markets varies by water basin. It is often a struggle to identify the exact timing, exact geographic location, and specific characteristics of the buyer and the seller of water trades, as well as the particular nature of the water rights involved. For studies of water prices and transactions, see Brown (2006) and Brewer (2008).

[15] See, for example, Dinar et al. (1998), Murphy et al. (2000) and Cummings et al. (2004).

[16] Libecap (2011), Ostrom (2011), Hanemann (2006)

[17] See Lixia et al. (2010), Knapp et al. (2003), Dridi and Khana (2005), Dinar et al. (1991).

In an effort to track the basic market forces at work, we want to consciously minimize the number of complicating factors, and choose the Rio Grande water market for our study. The Rio Grande market typically gets good reviews as a well-functioning market. [18] The water market is relatively thick and has low transaction costs. There are few concerns about externalities, and there are limited alternative water sources beyond the surface water that is traded. In this relatively favorable environment, we investigate how the crop composition changes with a water market. We include a whole battery of controls, taking into account county-, crop-, and year-specific factors and other time-varying factors that may differ between treatment and control counties. We also explicitly emphasize the implicit assumption behind the prediction of the impact of water markets, i.e., that water rights are initially misallocated in favor of lower-value crops.

Our difference-in-difference analysis reveals that markets increase the share of crops that are on average more productive in terms of dollar revenue generated per water used. Moreover, this effect is most pronounced during droughts. We use two dataset. One is relatively aggregate and compares the most-productive crops, fruits and vegetables, with all other crops. We also use more disaggregate data that does not include the most-productive crops. At the more disaggregate level, we show how specific crop characteristics such as drought resistance interact in interesting ways with a market. This enriches our understanding of agriculture's adaptation mechanisms also for non-irrigated crops. It turns out, e.g., that drought-resistant *non-irrigated* crops also become more prevalent in water-market counties that charge a price for water.

The paper is structured as follows. First, we describe the Rio Grande Valley market. Next, we discuss the framework that rationalizes the shift in crop production due to a water market. This section show how the initial distribution of water rights matters for the water reallocation and how water markets interact with water scarcity. We then discuss the empirical specification and our data. Finally, we discuss the estimation results and conclude.

1. The Water Market of the Rio Grande

One of the most established water markets in the United States operates along the lower and middle reaches of the Rio Grande. The Rio Grande river stretches from Colorado to the Gulf of Mexico (see Figure 1a and Figure 1b). The river constitutes the border between the United States and Mexico for 1,200 miles. The water market has been active since the early 1970s and encompasses 10 counties.[19] Both *The Water Rights Adjudication Act of 1967* and The *State of Texas vs. Hidalgo County Water Control and Improvement No 18* (1969) were critical for the establishment of the market. *Texas vs. Hidalgo County* was filed in 1956 by the Texas Attorney General. Its aim was to ensure sufficient water supply for domestic use and to prevent water

[18] See Leidner et al. (2011), Griffin (2011), and Section 1. Due to data constraints, comparisons across many water markets are only possible at a relatively aggregate level and in mostly in qualitative terms, see Grafton et al.(2011).
[19] How the Rio Grande market functions and how it came into being is described in Leidner et al. (2011), Griffin (2011), Chang and Griffin (1991), Schoolmaster (1991), Levine (2007), and Kaiser (1987).

districts, private corporations, and individuals from diverting water from the lower Rio Grande.[20] As is common, the establishment of a water market redefines water rights to facilitate trading. Our study of the effects of water markets is hence inextricably linked to the changing legal framework that made the water market possible.

A new and coherent apportionment of the valley's water resources was introduced to stem overuse. A procedure was put in place to resolve claims, acquire new water permits, and transfer permits. In addition, the *1967 Act* paved the way for the creation of the Rio Grande Watermaster's Office (RGWO). The RGWO is critical for the water market's operation. The priority *by seniority* which governs most of Texas was abandoned in the water market counties. We therefore expect farmers in market counties to be more flexible than their counterparts in the control counties. In case of a drought, older water rights holders of control counties retain their privileged access to water even if their water use is less productive. In market counties, however, farmers can reallocate water among themselves informed by who's willing and able to pay most. Note also that inter-sectoral priority *by use* is introduced in water market counties. It gives municipal and domestic users priority over industry, which in turn has priority over agriculture. As we focus on crops in agriculture only, inter-sectoral priority transfers out of agriculture should matter for our analysis only to the extent that they reduce water for agriculture. We expect such transfers out of agriculture in the post-market period to affect the crop composition in the same way that droughts do, moving water to more productive crops. [21]

The Rio Grande water market has taken off since the early 1970. Since then water rights can be transferred permanently or on a temporary basis. Only with permanent transfers does the ownership of the right change hands for good. Temporary, short-term contracts either run over a fixed term (like a year), or are a one-time sale. Permanent sales are mostly inter-sectoral from agriculture to cities. In spite of this, agriculture still holds 80% of the water rights (see Table 1). Moreover, water districts are reportedly increasingly reluctant to sell agricultural water rights. They prefer temporary deals.[22] It is hence not surprising that the spot market with one-time, intra-sectoral transfers in agriculture is especially active.

Students of the Rio Grande water market give it relatively high marks as an effective instrument to reallocate water.[23] First and foremost, the scarcity of water in the region makes it a valuable resource, and there is an incentive to buy and sell water rights. For our period, average

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[20]See http://tarlton.law.utexas.edu/rare/findingaids/texvhidalgo.pdf.

[21] Within irrigation rights there is also a differentiation between A and B rights. The 1969 suit defined the water rights in the lower Rio Grande. By 1984, water rights in the middle portion of the Rio Grande were defined in similar fashion (see Leidner et al., 2011). Irrigation rights are the only rights that allow for some banking of water over time. Depending on the level of the reservoirs and the drought conditions, the actual water allotment can be prorated, in which case one can only withdraw less than 100% of one's water right. Note that in times when water is plentiful, the RGW has been known to charge no price for withdrawal (see Chang and Griffin, 1991).

[22] Chang and Griffin (2002).

[23] See, Leidner et al. (2011), Schoolmaster (1991), Chang and Griffin (2002), and Levine (2007).

precipitation in the area was 488 millimeters, or 65% of the contiguous 48 states. In addition, the area population almost quadrupled since 1950 --It only doubled in the entire United States.

Water scarcity is, however, not sufficient for a water market to function. There must be opportunities to reallocate water over time or across activities. The Rio Grande valley has expanding cities whose average water productivity is high compared to agriculture, and in agriculture there is a wide variety of crops. Table 2 shows the main irrigated crops that have grown in the water market (and control) counties. Many credit the area's topography for the water market's persistence. Much of the diverted water does not return to the Rio Grande, which limits potential (negative) externalities that might impede a well-functioning market. Add to this the predominance of surface water whose rights are much better defined than groundwater.

Finally, there is the RGWO that, as Yoskowitz (1999) points out, effectively is a broker. RGWO brings together buyers and sellers. All (potential) market participants know RGWO keeps track of water balances for individual water-rights holders. It provides, either online or by phone, institutional information, data, and required forms, reducing search and transaction costs. Costs that relate to the paperwork and negotiations are fixed and low.[24] Spot-market transactions in agriculture are processed within one day since they do not involve a change of water use. Permanent and often inter-sectoral sales, on the other hand, require public notification. And finally, the RGWO officers patrol the river and canals, making sure right holders comply with regulations and don't pump water illegally.

The upbeat assessment of the Rio Grande market makes it a good venue for an in-depth empirical analysis. We want to document how water markets change the crop composition without having to untangle too many complicating factors. It is encouraging that Chang and Griffin (1992) and Leidner et al. (2011) report a shift toward higher-value crops which tend to be less water intensive/more productive. More analysis is needed, however. A shift toward higher-value crops in water-market counties, for example, could track a trend in the region, and need not follow from water markets. Similarly, an increase in corn in the water-market counties cannot be readily attributed to water markets, given an overall rise in corn. Conversely, a reduction in vegetable output need not contradict the predicted crop composition shift induced by water markets if control counties show an even stronger reduction. What we propose, therefore, is a difference-in-difference analysis that uses as treatment the counties that participate in the water market, and as control the neighboring counties that do not. We investigate the change in crop composition in the water-market counties relative to non-water-market counties before and after the water market is introduced. As we show below, the control counties do not only share the same climate due to their proximity, as a group, they also have comparable agricultural potential. Moreover, even though the treatment counties by default lie along the Rio Grande, the control counties have similar access to water – For one, the Nueces , a major river in Texas,

[24] Watermaster website: http://www.tceq.state.tx.us/permitting/water_rights/wmaster/rgwr/riogrande.html.

and its main tributaries, as well as the tributaries from the Rio Grande run through the control counties, see Fig. 1b.

Assessing the impact of water markets by studying the actual uses of water—in our case, the particular crops that are produced—has an additional benefit. Our analysis complements work with water-market transactions. At same time, we sidestep some of the challenges that are associated with studying water-transaction data directly.[25] As many have noted, the quality of the water-transaction data varies greatly. One often cannot retrieve the exact prices, distinguish actual transactions from gifts (with price zero), or identify the buyer or seller of the water rights by location and/or economic activity.[26] In addition, oftentimes only a subset of the water transactions is available. It is not uncommon that permanent sales are recorded, whereas temporary leases are not. This is a challenge if buyers of water rights lease back some of the acquired water.

2. Conceptual Framework

In this section, we focus on the basic prediction that water markets move water from (on average) lower- to higher-value activities. The latter is short for moving water from activities that use more (non-water) production factors per unit of water to ones that use less, or, in terms of our empirical work, from activities with on average lower productivity (less $ revenue generated per unit of water) to ones with on average higher productivity (more $ revenue generate per unit of water). To contrast high- versus low-value activities, one typically considers vegetables versus hay, or city output versus agricultural production. In a stylized but well-established two-sector, general-equilibrium framework, we specify under what conditions this basic prediction holds, and what is assumed about the initial distribution of water rights. Inspired by this setup and by the contrast it draws between a world with and without water markets, we present our empirical specification in Section 4.

We describe the impact of an adverse shock such as a severe drought in a specific-factors model with and without water markets. Specific-factors models, either explicitly or implicitly identified as such, are often used to discuss water markets.[27] Ours is a specific factors model with two sector and two factors in a small open economy with perfect competition in both the production factors and commodities markets. This model that operates in an international environment has a distinct record in international economics. Its short- and long-run impacts are well understood, and it is nice that prices of the relatively homogenous commodities are pinned down by

[25] See Chang and Griffin (1992), and Heade (1999).

[26] Because of data limitation, Chang and Griffin (1992) and Heade (1999) rely on survey data of a subset of the transactions to evaluate the economic gains associated with representative transactions from agriculture to cities.

[27] See Colby,B. (1990), Easter et al. (1998), and Griffin (2006).

international markets.[28] What defines a specific-factors model is that some production factors are not mobile between sectors in the short run. In our agricultural region one sector produces high-value crops (vegetables), and the other low-value crops (hay). Our main objective is to compare what happens in response to a drought when water can be transferred between hay and vegetables (i.e. when there is a water market) with when it cannot.

The two factors we consider are water, W, and capital, K – Capital is a composite factor that includes both physical and human capital. Vegetables and hay need K and W and have a neoclassical constant-returns production function $Y_c = f_c(K_c,W_c)$, $c = h,v$. We assume that low-value hay uses far less capital per unit of water compared to vegetables, i.e., $K_h/W_h < K_v/W_v$.[29] As is standard, there is no inter-regional factor mobility: Capital and water cannot leave the region. And all resources are used in the region, i.e., $K = K_c + K_v$, and $W = W_c + W_v$, where K and W amount to the region's capital and water For ease of exposition, we assume there are no long-run frictions in the economy: Capital and water can freely move between the two crops in the long run. In the short run, however, this mobility is not guaranteed. Capital stays with its original crop in the short run. Water can move between hay and vegetables only when there is a water market.

Now consider a drought which we model as a drop in our region's available water, W, all else equal. We assume the drought has no impact on international prices and demand. The long-run outcome is well known: The low-value crop takes the brunt of the shock, to such an extent even that its output may decrease so much that the high-value crop actually increases in output. This is the familiar Rybczynski (1955) effect. The short-term effect is less extreme. Both crops decrease in output. Moreover, the larger the differences in K_c/W_c between hay and vegetables, and the more similar the substitutability between water and capital, the more likely it is that the output of the low-value crop (hay) will indeed shrink most.[30]

Figure 2 represents the outcome graphically. The downward-sloping line on the left represents water demand by vegetable farmers for a given amount of capital or water's-value marginal product. The upward-sloping line mirrors a regular demand curve (the amount of water demanded is measured from the origin on the right). It represents water demand for hay.[31] The length of the x-axis captures all water in the region. We assume for simplicity that point A, at

[28] See seminal papers by Mayer (1974), Mussa (1974), and Neary (1978). For a textbook version of the model, see Krugman et al. (2012), p.51-63, 91, and Feenstra (2004), p.64, 72–75.

[29] In the setup we consciously want to steer clear of "water intensity" which is often defined in the literature terms in purely physical terms as water per pound or water per hectare -- almost devoid of economic value creation. For this reason, we consciously do not choose land as second factor next to water, and we intentionally compare the two crops in terms of their capital/water ratio, rather than their water/capital ratio, or their water intensity. K stands for us for all (non-water) factors.

[30] See Neary (1978). Bhagwati et al. (1998), p. 157 (10.50), derives the exact condition to determine which sector decreases most. The sector with the lowest K/W always shrink most if there is an equal elasticity of substitution between water and capital for both crops (as with Cobb Douglas), or when the elasticity of substitution is highest in the low K/W sector. When the elasticity of substitution is highest in the high K/W sector, one needs a sufficient difference in the K/W ratios of the two sectors to ensure that output of the low K/W sector decreases most.

[31] The figure draws on Neary (1978).

which the two demand curves intersect, corresponds to the long-run equilibrium. When the amount of water in the region shrinks, the base shrinks, and the right y-axis shifts to the left with the amount of the water reduction. Note that the right demand curve shifts to the left exactly with the same amount. With a water market water can freely flow to where its price is highest. In this case, the new allocation coincides with point *B*, for which both crops' effective water use shrinks. In our particular example, vegetable water use shrinks less than that of hay.

To understand water markets, let's study how the initial distribution of water rights constrains water use. Let everyone own just enough water rights to produce their initial output. Consistent with the Rio Grande before the water market, as well as with the rest of Texas, we allow for senior rights. First, let the hay farmer's rights be senior. In this case, the hay farmer has priority access to water if *W* decreases in the region. With no water market, the drought may not affect how much water the hay farmer uses. Nor may it affect his output or the value-marginal productivity of the last unit of water he employs. 0^1_HC equals hay's initial amount of water, $0^0_H A$. Hay's value-marginal product stays at P_{W0}. In this case, the vegetable farmer bears the full brunt of the drought with available water shrinking from 0_VA to 0_VC. Without a water market, he has to make do with less water and his output plummets. Water's value-marginal productivity for vegetables is then higher than for hay ($P_{WC} > P_{W0}$). The vegetable farmer would be willing to pay more than hay's marginal value product, P_{w0}. Now, consider the opposite initial water-rights distribution and its very different outcome without a water market. If the vegetable farmer has senior rights, the hay farmer is hit hard. Water available for hay drops from 0_{0H} *A* to 0_{1H} *A*, and hay's value-marginal product of water rises (from P_{W0} to P_{WA}). The hay farmer would be eager to buy water.

Our analysis has a few implications. With increased water scarcity and a water market, we expect the high-value sector to increase in the short run relative to the low-value sector. Water should hence flow to where it has the highest (marginal) return. In the absence of friction, we end up in the long-run equilibrium point *B*.[32] We have shown that it is critical that low-value crops have senior rights for water to flow to high-value crops. Only then do high-value crops have the highest value-marginal product. In sum, if one predicts that water markets increase the output of high-value crops under scarcity, and that water rights will be sold by low-value to the high-value crops, it is implicitly assumed that water rights are biased towards low-value crops initially. While this assumption is often not made explicit, it may be justified for historical reasons. Farmers with enough water may have continued to grow the low-value crops they grew before water became scarce. Similarly, when applying the model to cities versus agriculture, lower-value agriculture has historically held most water rights.

[32] In the absence of transportation costs, the final outcome is independent of the distribution of water rights, which is consistent with the Coase Theorem.

3. Data

Our water market includes 10 counties at the lower and middle portions of the Rio Grande, see Figure 1a and 1b. Since the counties along the river constitute the U.S.-Mexican border, we choose its U.S. neighbor counties to the east as controls. Due to the geographic proximity, the climatic conditions of control and treated counties are quite similar. The controls are also similar in terms of agricultural potential. For the set of crops that we study, we find virtually no statistical difference between control and treated counties for three FAO indices: the agro-climatic potential yields, and the agro-ecological suitability values applied to, on the one hand, rainfed and, on the other hand, for irrigated crops, see Appendix Table 11. Moreover, as one can see from Figure 1b, the counties have similar access to water. While the treatment counties lie along the Rio Grande, some of its tributaries as well as the Nueces, a major river in Texas, and its tributaries run through some of the control counties. We will also test the robustness of our results by expanding the control group with 12 additional neighboring counties.[33] Note that in the final analysis, we exclude the counties Uvalde, Atascosa, and Medina from the baseline and expanded control group since they are part of the more recent water market above the Edwards Aquifer that was established in the 1990s. This leaves us with 9 counties in the baseline control group and 19 counties in the expanded control group.

The adjudication of water rights was completed in 1971 for four counties in the lower reaches: Cameron, Willacy, Hidalgo, and Starr. For the remaining six counties in the middle—Zapata, Jim Hogg, Webb, Dimmit, Maverick, and Kinney—adjudication by the Texas Water Commission was completed in 1984 (Leidner et al, 2011). In one specification, 1971 marks the beginning of the post market period for all 10 counties. In our preferred version, we use 1971 for the lower reaches and 1984 for the middle reaches. Note that first approach could be justified by expectations and Appendix Tables 6–10 report the results. [34]

Our main data source is a county-level panel from the USDA *Census of Agriculture and Population*, which is collected approximately every five years between 1954 and 2012.[35] We extract two datasets. One is relatively aggregate and gives us for three categories of crops (fruits, vegetables, and all other crops) consistent measures on the total area that is harvested and irrigated for that crop as well as the overall (irrigated and non-irrigated) dollar value of the crop. The advantage of this dataset is that it captures all crops while singling out those that are most productive

[33] The similar results with this expanded control group are shown in Appendix Tables 1-5.

[34] Allowing the water market to kick in at two points in time implies that we use for the years between 1971 and 1984 the middle-reach counties (which did not yet have a water market) as control counties for the lower reaches (which did have a water market).

[35]The exact dates of the published data are 1954, 1959, 1964, 1969, 1974, 1978, 1982, 1987, 1992, 1997, 2002, 2007, and 2012. We relied on "Historical, Demographic, Economic, and Social Data: The United States, 1790–2002 (ICPSR 2896)" by Michael R. Haines, Colgate University, via Inter-university Consortium for Political and Social Research at the University of Michigan. We supplemented the data with newer waves of the same census in 2007 and 2012 from USDA's online publication. Specifically, the 1969 and 1974 Censuses only collected data on total irrigated areas for all crops as well as total harvest areas for a few crops (corn and sorghum in 1974 and hay in both years) from larger farms with sales over $2,500 (or Class I-V farms). To make the data from these two years comparable, we scaled the variables by multiplying with (total cropland area/total cropland area in Class I-V farms. Moreover, the irrigated areas for fruits are not reported from 1978 to 1987.

compared to the less productive "other crops." This dataset will be ideal to investigate whether indeed the most-productive and thus higher-value crops become more prevalent compared to the less-productive water ones when there are water markets as opposed to when there are none.

We also consistently collect more disaggregate data for five crops from 1954 to 2012. These data, do not cover all the crops—they do not include the most productive crops. Studying these crops also reveals the challenge of using more disaggregate data. The issue arises how to handle specific characteristics of the crops such as their drought resistance that may interact with water markets. In particular, drought resistance may make it possible to grow crops without irrigation with expensive water. Corn, sorghum, wheat, hay, and cotton are in this group.

We construct a proxy measure for a crop's average (water) productivity as (real) sales over water use. We rely on a document from the *Food and Agriculture Organization*, Brouwer and Heibloem (1986), to provide an approximate measure of the quantity of water needed for each crop's harvest area. We combine the measure with the harvest areas and the total market values for vegetables, fruits, and all other crops that we consistently extract from the USDA data from 1954 to 2012. Formula (1) makes explicit our approximate real water-productivity measure for crops *c* in year *t*.[36]

$$Water\ Productivity_{ct}(\$/m^3) = \frac{Market\ Value_{ct}(1969\ \$)}{Harvest\ Area_{ct}(Acre) * Water\ Needed_{ci}(m^3/Acre)} \quad (1)$$

Keep in mind that this is a crude measure. Ideally, one would want a measure of the total value added for the crop, which is simply not available for agricultural data. In addition, for a study such as ours that involves irrigation, it is worth pointing out that the quantity of water needed here is not the actual quantity of irrigation water used. To be explicit, the average market value per harvest acreage is not the marginal value of irrigation water. Given the data limitations, this is the closest approximation possible and the values for our crops are shown in Columns (1)–(3) of Table 3. Note also that the productivity measure does not vary by county.

As for the second disaggregate set of five crops in our analysis, the crops resort under the "all other crops" category of the aggregate data set. Their market value is not available in the *USDA Census* from 1954 to 1964, which is why we do not have a consistent measure for market values for the entire period. We, therefore, construct an estimate of the market value for crop *c* in year *t* using the output data in the *USDA Census* and the price data from USDA Feed Grains Data: Yearbook Tables (2015) as follows:

$$\widehat{Market\ Value}_{ct}(\$) = Market\ Price\ in\ Texas_{ct}(1969\ \$/ton) \times Output_{ct}(ton) \quad (2)$$

Subsequently, we plug this estimated market value into formula (1) and obtain the water-productivity measures from Columns (4)–(8) of Table 3. Consistently, hay is the least (water) productive crop. To be explicit, given the different ways in which the productivity measures are

[36] We deflate with the CPI that has 1969 as base year.

constructed for the two sets of crops, the numbers in Columns (1)–(3) are not directly comparable with those in Columns (4)–(8).

We also rely on annual precipitation and temperature data from the monthly, global-gridded, high-resolution point data (0.5-degree latitude × 0.5-degree longitude global grid) provided by the *Center for Climate Research* at the University of Delaware. The data are based on work by Willmott and Matsuura.[37] Since the revenue for some crops may depend on precipitation in the previous year, we report the average of two years (the survey year and the year before).[38] The temperature measure that we use as additional control variable comes from the daily temperature data collected by the *United States Historical Climatology Network* (USHCN) from 1,218 stations across the contiguous United States. To translate those station-level data into variables with the geographical circumscription of counties, we use the standard Inverse Distance Weighted (IDW) interpolation. The latter implicitly assumes that closer observations tend to more alike. With this method, we generate raster data (with a numerical value estimated for every pixel on the map) for each year using GIS tools. Then, we calculate the average within each county boundary.

Figure 3 presents the average of the county-level precipitation at five-year intervals. The right-hand y-axis is the axis of reference for this measure. We also construct a measure of drought that equals 1 if the annual precipitation is smaller than the long-term (1954–2012) mean minus the long-term standard deviation for the entire period in the county, and 0 otherwise. The vertical bars (measured on the left axis) indicate the fraction of the counties that are in a drought. As one notices, the 1970s, 1980s, and 1990s are relatively wet, while the early 1950s and the most recent years represent a severe drought for virtually all the counties.

4. Empirical Specification

We employ a difference-in-difference strategy to identify the impact that water markets have on the type of crops that are grown and whether there is a shift toward the more-productive crops in the counties with a water market compared to the control counties without.

Our primary fixed-effects regression of interest is expression (3).

$$
\begin{aligned}
Share_{cit} = {} & \alpha_c + \alpha_t + \alpha_i + \alpha_c \times \alpha_t \\
& + \beta_1 Watermarket_i \times Post_t \times Real\ Water\ Productivity_{ct} \\
& + \beta_2 Watermarket_i \times Post_t + \beta_3 Watermarket_i \times Real\ Water\ Productivity_{ct} \\
& + \beta_4 Post_t \times Real\ Water\ Productivity_{ct} + \beta_n X_{ncit} + e_{cit} \qquad (3),
\end{aligned}
$$

[37] http://climate.geog.udel.edu/~climate. We use *Monthly Total Precipitation: Time Series (1900–2014).*

[38] This is potentially an issue for the earlier years of the census.

where *c* refers to crop, *t* to year, and *i* to county.

On the left-hand side, we measure crop *c*'s share in county *i* in different ways in order to capture the change in composition over time. We respectively consider:

- the irrigated area of crop *c* in county *i* as a percent of the *total* farmland area in county *i* at time *t.*
- the non-irrigated area of crop *c* in county *i* as a percent of county *i*'s *total* farmland area at time *t*.[39]

The measures capture *across* crops how likely it is that a particular harvested crop is irrigated or not on the total farmland in a county. The first variable is directly relevant for water markets as they directly provide water for irrigation. The second variable matters for two reasons. On the one hand, we want to see whether what happens to non-irrigated crops is different between market and non-market counties. In addition, we may be able to extend some of Hornbeck and Keskin (2014)'s findings about farming's adaptation in light of water stress. Therefore, we study how crop characteristics such as drought resistance interact with water markets and droughts, and whether these interactions differ between irrigated and non-irrigated crops.

Regression (3) includes a whole battery of crop, county, and time effects as well as time x crop effects, and a set of interactions. In our formulation of regression (3) we include all the fixed effects explicitly to make the interpretation of the many interactions easier.

The interactions combine the variables $Post_t$, $Watermarket_i$, and $Real\ Water\ Productivity_{ct}$. $Post_t$ is a dummy for the years since the water market was introduced, $Watermarket_i$ is a dummy that marks the counties that have a water market, and $Real\ Water\ Productivity_{ct}$ captures the real water productivity per crop as it varies over time. $Post_t$, $Watermarket_t$, and $Real\ Water\ Productivity_{ct}$ do not enter the regression separately as they are respectively subsumed under the year, county, and year x crop effects. The X_{ncit} variables bring in the time-varying characteristics of the counties and crops. We estimate the regressions with weighted least squares, where we use as weights the county-level average harvest area for each crop in pre-market years. e_{cit} is an idiosyncratic error term clustered at the county level.

The primary coefficient of interest is the coefficient β_1 of the triple interaction of dummies for counties with water markets, years after the introduction of the market, and crop real water productivity as measured in 1969 dollars in revenue per cubic meter of water. Note the benefit from working in levels (and not logs) is that we can investigate for all crops the impact of, say, a 1 \$ per m^3 increase in productivity, which is a meaningful measure from the perspective of the farmer deciding to allocate water optimally. Note that we have calculated the relative water productivity for each crop by subtracting the productivity of the least-productive crop for each year. Because of this, β_2 gives the average baseline effect estimated at the annual lowest water productivity. Our basic hypothesis suggests that we should obtain a positive coefficient for β_1.The

[39] The non-irrigated area is obtained by subtracting the irrigated area from the harvested area.

coefficient β_1 then shows the estimated average percent-point increase of the share of irrigated area in farmland due to an increase by one dollar per cubic meter in productivity from the baseline (least-productive) crop once the water market is established. To measure the full impact of introducing a water market, one needs to add together (β_1 × relative water productivity) and β_2. As we have included all the components of the interaction separately, we ensure that our findings are not driven by the effect of introducing a market per se, by productivity trends across all counties in the post-water-market period, or in the water-market counties independent of the introduction of a water market.

In addition to precipitation and the degree-day counts, we also add a set of control variables that includes county-level logarithmic values of total farmland area, pasture area, and the per acre revenue from pasture. When estimating the same equation with a subset of all the crops (i.e., with the disaggregate data set), we in addition control for the logarithmic values of the sum for all crops excluded from the subset on harvest area, irrigated area, and total revenue. The reason for controlling for these variables is that we want to see if the results are robust conditional on alternative usage of the farmland. To alleviate the concerns of potentially differential pre-market trends of the outcome variables before the establishment of the water market, another set of control variables is used. In particular, we insert the specific outcome variable for each regression as specified below in pre-market years (1954, 1959, 1964, and 1969) interacted with the dummies for each post-water-market year, following similar empirical specifications as in Hornbeck (2012).

Regression (4) is the most comprehensive and also the most complicated regression. It brings in the impact of droughts. $Drought_{it}$ equals 1 if annual precipitation in a county is less than the long-term mean minus the long-term standard deviation in that county, and equals 0 otherwise.

$$
\begin{aligned}
Share_{cit} = \quad & \alpha_c + \alpha_t + \alpha_i + \alpha_c \ x \ \alpha_t \\
& + \beta_1 Watermarket_i \ x \ Post_t \ x \ Real\ Water\ Productivity_{ct} \\
& + \beta_2 Watermarket_i \ x \ Post_t + \beta_3 Watermarket_i \ x \ Real\ Water\ Productivity_{ct} \\
& + \beta_4 Post_t \ x \ Real\ Water\ Productivity_{ct} \\
& + \beta_5 Watermarket_i \ x \ Post_t \ x \ Drought_{it} \ x \ Real\ Water\ Productivity_{ct} \\
& + \beta_6 Droughts_{it} + \beta_7 Watermarket_i \ x \ Drought_{it} + \beta_8 Post_t \ x \ Drought_{it} \\
& + \beta_9 Drought_{it} \ x \ Real\ Water\ Productivity_{ct} + \beta_{10} Watermarket_i \ x \ PostDrought_{it} \\
& + \beta_{11} Watermarket_i \ x \ Drought_{it} \ x \ Real\ Water\ Productivity_{ct} \\
& + \beta_{12} Post_t \ x \ Drought_{it} \ x \ Real\ Water\ Productivity_{ct} + \\
& + \beta_n \mathrm{X}_{ncit} + e_{cit} \qquad (4)
\end{aligned}
$$

We are particularly interested in the coefficient β_5 of the quadruple interactions. A positive coefficient should tell us whether an increase in the water productivity of a crop affects the crop composition, and whether it is indeed the case that droughts make it more likely that water is given to the overall-more-productive crops.

To make sure our findings are not spurious, we include all the interactions of the components of the quadruple interaction. With those additional interactions, one has to be a bit careful to interpret the impacts correctly, and also to reinterpret some of the coefficients compared to previous specification (3).

Because of the new interactions with $Drought_{it}$, for example, the coefficient on $Watermarket_i$ *x* $Post_t$ now explicitly captures the impact of having a water market when there is *no* drought, and so does $Watermarket_i$ *x* $Post_t$ *x Real Water* $Productivity_{ct}$. To measure the full impact of introducing a water market, one needs to add together β_2, β_{10}, and ($\beta_1 + \beta_5$) × relative water productivity.

5. Results

Consider a first set of estimates in Table 4. Table 4 uses the first, relatively aggregate dataset that covers all crops, including the most (water) productive ones (vegetables and fruit) that are singled out from the 'other crops.' To be explicit, 'other crops' stands for all crops minus the most productive ones. We first focus on the irrigated area of a crop as a percentage of farmland as the dependent variable. There are three blocks of estimates, and within each block, moving from left to right, the specifications vary as we increasingly insert more control variables. We put most weight on the third column in each block. It includes a whole set of pre-water-market controls, including as in Hornbeck (2012) the outcome variables in 1954–1969 interacted with dummies for the post-market years. The latter controls should most clearly capture any pre-existing trends.

In the first block, we just check whether water markets tend to affect the irrigation area, for which we rely on regression (3) with the *Post × Watermarket* interaction but without the water productivity-interaction terms. While there is a slight negative tendency for all three specifications, it turns out that there is no significant way in which water markets affect the irrigation area per se across all crops. In the second block, we present the estimates of regression (3) with the critically important triple interaction of *Post × WaterMarket × Real Water Productivity*. The productivity interaction variable has a positive and significant coefficient across all the three specifications in the second block. The positive sign confirms the basic prediction associated with water markets. All else equal, water markets give rise to an increase of the share of more-productive crops. To be precise, relative to the least productive crops ("other crops"), a $1-per-cubic-meter increase in water productivity should give rise to an increase of more than 2 percentage points in the irrigated area as a share of farmland, which is about half of the within-county standard deviation.

In the third block, we present the most comprehensive estimates of regression (4) with the additional interaction for when there is a drought. Comparable to the first block, we find that the initial triple interaction with water productivity also has a positive and significant impact here. Note, however, that the interpretation of the triple interaction in regression (4) is slightly different because of the added quadruple interaction with drought. The coefficient of around 1.5 implies that relative to the least-productive ("other") crops, a $1-per-cubic-meter increase in water productivity should give rise to an increase of 1.5 percentage points that goes to more-productive crops *in non-drought or wet years*. We estimate a positive and significant coefficient on the quadruple interaction of *Post × Watermarket × Drought × Real Water Productivity.* The coefficient indicates there is an additional, relatively large percentage-point increase in the share of irrigated crops that is cultivated relative to the "other crops" when there is a drought – In the first two columns of the third block there is an across- the board negative effect on the crop share due a drought which has to be taken into account to calculate the overall effect; the across-the-board effect is not significant in the last column. What our quadruple interaction indicates is that the shift toward higher-value or more (water) productive crops is even more pronounced in years of a drought.

Note that there is an alternative way of reading these estimated effects possible. Instead of seeing them as reflecting the merits of market flexibility, one might read into them the relative inflexibility of a water rights system dominated by seniority in the neighboring counties. Those control counties have no market and are governed by seniority that may withhold water from more-productive crops. By way of example, if in non-market counties the least (water) productive crops held most of the water rights, the more-productive crops may be hammered in the absence of trading, see Libecap (2011). In this way, the interaction with drought puts on display the resilience of water markets that are able to respond to changes in external circumstances in a way that counties that cannot trade are not able to.

In Table 5, we turn to non-irrigated crops. We want to check whether some of the findings for irrigated crops, which should be the primary beneficiaries of the water from water markets, carry over to non-irrigated crops. Table 5 is set up in the same way as the previous Table 4. There is no significant increase in the overall crop area of non-irrigated crops in the post-water-market years. This is consistently the case as we add more control variables in Columns (2) and (3) of the first block. In the second block, we do see an increase in the non-irrigated area of more-productive crops in the water-market areas. Interestingly enough, in the third block, the increases in the share of non-irrigated, high-productivity crops in response to a drought remains significant albeit only at the 90% level in the last two columns with most controls. These findings suggest, on the one hand, that in counties where water has an explicit price, there seems to be a more general push toward more-water-productive crops, which includes non-irrigated crops. However, the benefit of highly productive irrigated crops is most pronounced in water-market counties, especially during droughts. Note that qualitatively similar results are found when we increase the set of control counties (including the neighbors from neighbor counties), see Appendix Tables 1–5.

In a double-difference analysis that has a fixed effect for both the market and non-market counties, there can be systematic differences between the counties that we study. The validity of our analysis, however, is especially sensitive to any existing pre-market trends that could explain the differential impact between treatment and control counties. Of particular interest is to know how production of the more productive crops in both the treatment and control countries evolved relative to the less productive crops. We refer the reader to Figures 4 which focus on the period *before* the water market was put in place. Figure 5 takes us through the whole period.

Figure 4 has four panels for the first, more aggregate data set. The upper panels on the left compares unconditionally the raw data for the pre-market years for the irrigated crops in both the treatment and control counties. We are in particular interested in the ratio of the (irrigated) acreage of vegetables, the most productive crop, relative to the (irrigated) acreage of the less productive crops, "all other crops." [40] This ratio should signal whether indeed there is an increase in more productive crops relative to all others once a water market is in place, and how this compares to what happens in the control counties. For our analysis to be credible, we do not want any pre-existing trend difference between treatment and control counties. On the right side, we compare the residuals for the same variables for the two sets of counties while conditioning on our whole battery of controls.[41] As one can see, even though we were careful to choose similar treatment and control counties, there is a bit of a trend difference in the unconditional plots for treatment and control on the left. Once we use our controls, however, we obtain virtually parallel lines for both groups on the right.

In Table 6, we also report statistics that indicate how the cross-section of treatment and control variables may differ. In particular, in Table 6, we report the results of a whole set of regressions of a long list of pre-market county characteristics on a dummy variable for the water-market counties, comparing the water-market counties and either their neighboring control counties in Columns (1) and (2) or the expended control counties (as identified in Figure 1a) in Columns (3) and (4). From the table, one can see that the water market counties have slightly less pasture than the control counties, but otherwise there is almost no statistically significant differences above 95% level. To be explicit, in our difference-in-difference analysis that includes county fixed effects, it is not the case that there cannot be any cross-county differences. It is critical that the time trends can be controlled for.

Figure 5 is especially relevant for the results that we obtained so far, as it compares treatment and control counties along a dimension that is critical for our result that water markets change the composition towards more productive crops. We present the ratio of acreage for the most productive crop over the least productive "all other crops" for the entire period. We focus on the

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[40] To draw the graph, we restrict the sample to a balanced panel. Due to some missing observations, we focus on vegetables without fruit. Note that the estimates for a balanced panel are qualitatively similar.

[41] To be explicit, the residuals for vegetables and "other crops" are obtained by running regression (3) without any of the interaction terms with $\textit{Water Productivity}_{ct}$. We weight the residual by the average pre-market shares.

version with controls. The pre-market period is identical to the upper-right panel of Figure 4. As one notices, from the mid-1990s onwards there is a widening gap between treatment and control counties as far as the ratio of vegetables to "other crops" is concerned. In other words, as we get to the end of the period there is an ever stronger shift towards productive crops in the water market counties. What is striking is that no such shift in the control counties. It is the case, however, that this shift is most pronounced in recent decades and cannot be identified from the very moment the market starts operating. The most likely explanation for this delayed impact stems from the regression (4) results discussed above and from Figure 3. On the one hand, droughts amplify the shift towards high-productivity crops. On the other hand, droughts are more prevalent in the early and later years of the sample. In other words, it is not all that surprising that during "wet years" (the 1970s, 1980s, part of the 1990s) there is not a very pronounced difference between treatment and control counties.

In what follows, we now turn to our slightly more disaggregate analysis, which, however, does not cover all the crops. The set of crops that we consider here does not include the most-productive crops, such as vegetables and fruits. There is a marked difference in some of the relevant characteristics of the five crops that we study through time. In particular, sorghum and cotton are, according to the FAO, drought-resistant crops, whereas corn, wheat, and hay are not. Our analysis indicates that it is necessary to take such differences into account. This section clarifies the challenges of identifying the basic hypothesis that we are investigating when certain crop characteristics vary. At the same time, our findings are suggestive of how some crop characteristics, in particular drought resistance, may interact with the emergence of a water market and the occurrence of droughts, and how changing circumstances (i.e., a drought) may determine which crops are deserving of (expensive) additional water.

In Table 7, we have two blocks of results for regressions with irrigated land as a percentage of farmland on the left-hand side. As before, within each block, from left to right, we introduce more control variables. In the first block, we introduce an interaction *of Post × WaterMarket × Drought Resistance* to study how drought-resistant crops interact with the introduction of a water market. As one can see, there is on average no significant impact on the area share that drought-resistant irrigated crops occupy when a market is introduced. The results in the second block, however, clarifies this finding somewhat. In the second block, we have introduced the additional interaction between drought-resistant crops and drought. As one can see, during periods of drought, the irrigated area of drought-resistant crops actually shrinks compared to all other crops around 3 percentage points. These findings are quite different from what we estimated in Table 8, which focuses on the *non*-irrigated crops.

For non-irrigated crops, we again have two blocks. We notice that drought-resistant, non-irrigated crops do respond differently from the non-resistant crops in the water-market counties where water has a price and water use is capped. There is an increase (not a decrease) here in the order of more than 3 percentage points of the non-irrigated area of drought-resistant crops when there is a water market in place. In addition, this increase is even stronger when we separate out periods of drought. These findings are of interest in light of Hornbeck and Keskin (2014)'s findings that areas that are not above the Ogallala Aquifer, and that as such do not have ready access to irrigated water, retained more drought-resistant practices. Our findings deepen these observations in the institutional context of a water market. We find that greater access to expensive water that can be more readily traded in a water market gives way to a *reduction* of drought-resistant crops that are irrigated. At the same time, however, we notice that those counties that have a water market in place will choose to *increase* the fraction of drought-resistant crops that are *not* irrigated compared to counties that do not have a water market.

Figure 6 complement Figures 4. They document for our more disaggregate crops the ratio of drought resistant (sorghum and cotton) crops compared to the other crops (corn and hay) for treatment and control counties. Once we introduce a whole battery of controls, it is clear that there is no pre-market trends.[42][43]

Finally, for completeness, Table 9 replicates our findings for the interaction of water productivity and water markets for the group of crops (corn, wheat, and hay) that excludes drought-resistant cotton and sorghum. For this relatively homogenous group of crops, we replicate our main finding. We see that higher water productivity is associated with increasing shares of irrigated crops. Here again, the effect is amplified when we consider drought versus non-drought periods.

Conclusion

One of the main challenges the world faces is to ensure economic growth and rising standards in living with a limited amount of freshwater for which there is increased competition. The only way to achieve this is to limit overall water use in order to prevent further depletion of water resources or environmental degradation and to increase the productivity of water's use. In light of the mounting water challenges, water markets that make the exchange of water rights possible are receiving much attention. Along both dimensions, water markets potentially have a role to play. For one, they put a cap on overall water use. In addition, they are expected to increase overall water productivity. Indeed, water markets should give way to a gradual shift in

[42] To draw the graph, we want a balanced panel. Due to some missing data for wheat, we exclude wheat from the graph. Note that our estimates for a balanced panel are qualitatively similar.

[43] There is no easy complement to Figure 5 for our most pronounced result involving non-irrigated, drought resistant crops and how they behave differently between water market and control counties, and how droughts amplify the difference. Figure 5 takes the ratio of two types of crops. Unfortunately, in the case of drought resistant and non-drought resistant crops, for the residual version of the graph (with controls, not the raw data) we find residuals that change signs, which confuses the picture. During the drought years residuals are more negative for non-irrigated drought resistant crops than for non-drought resistant ones in control counties. In water market counties, we see positive residuals for drought resistant crops and negative ones for non-drought resistant crops.

production from low- to high-value activities, which is short for activities that generate little value added per unit of water to ones that generate more.

There is an established literature that documents, often with simulations, the potential efficiency gains water markets should bring about. Our analysis is, to our knowledge, the first one to assess the actual impact of water markets on the ground within a difference-in-difference framework. We choose the Rio Grande water market in Texas for this exercise. It is one of the longest-functioning water markets in the United States. Moreover, we have the data to analyze its impact from a long-run perspective by comparing the change in the crop compositions between water market and control counties, before and after the water market was installed.

We find that water markets can indeed bring about a shift toward crops that are on average of higher value (more productive). This evidence confirms not only a basic and widespread hypothesis about water markets. The observation is also consistent with the prior that more water rights tend to be concentrated in lower-value crops than is justified on the basis of their productivity. We also find that the shift toward higher-value crops is most strongly observed during droughts. We also note that water markets have secondary effects. Water markets seem to more generally induce a shift toward more-productive crops, not just for irrigated, but also for non-irrigated crops that, strictly speaking, do not depend on irrigated water from the market. In addition, we also observe that water markets give way to more drought-resistant, *non*-irrigated crops.

Our findings of how water markets function are an important first step that asks for more empirical research. In particular, one may wonder how scalable water markets are and whether the more extensive use of water markets in Australia's Murray Darling Basin or in Chile produce discernable shifts to more-productive activities on a more aggregate level. In addition, and this is especially important since so many cities lie in water-stressed water basins, one may wonder whether similar effects could be detected from water transfers between agriculture and the more-productive cities.

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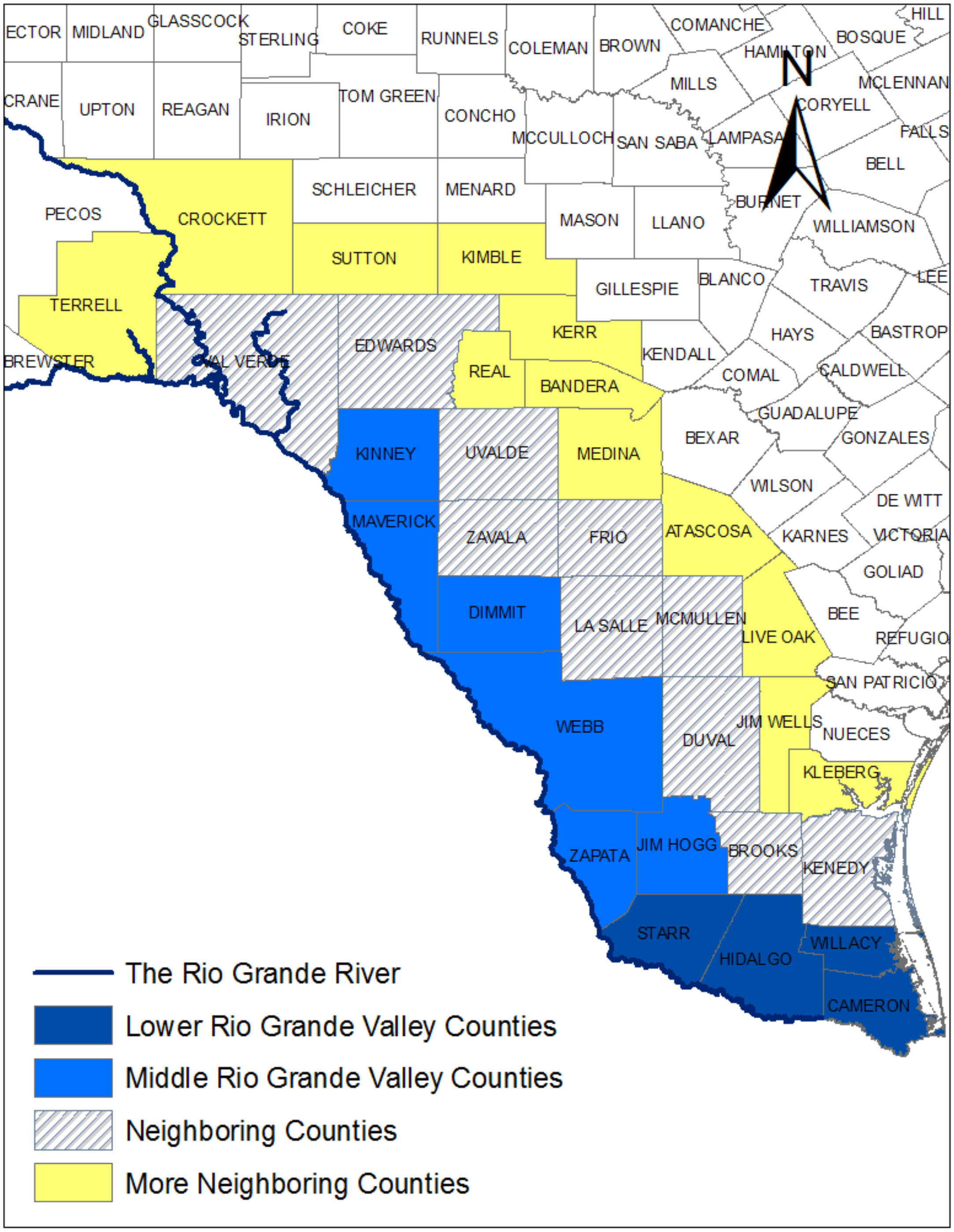
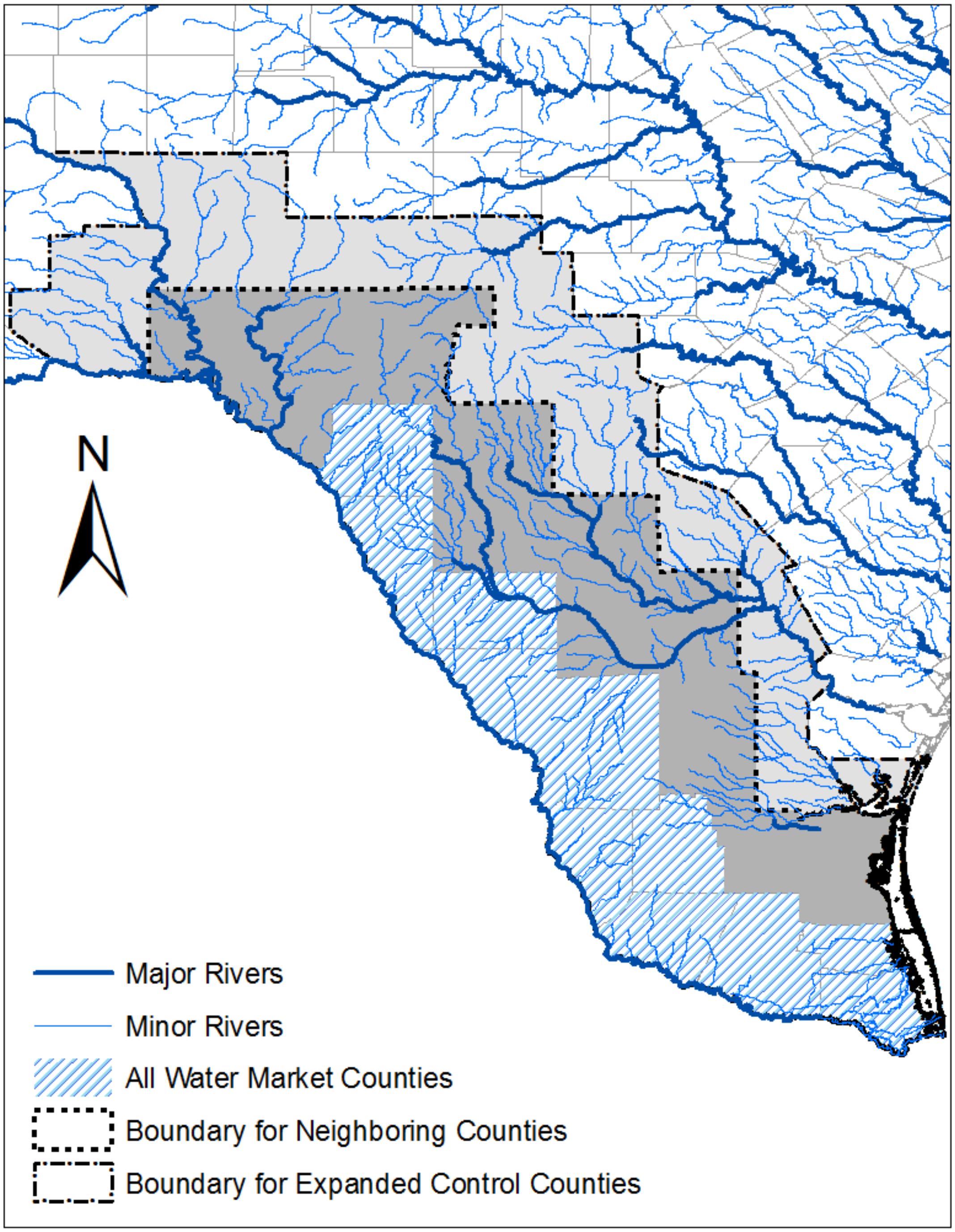
Figure 1a: Counties in the Rio Grande River Valley Area



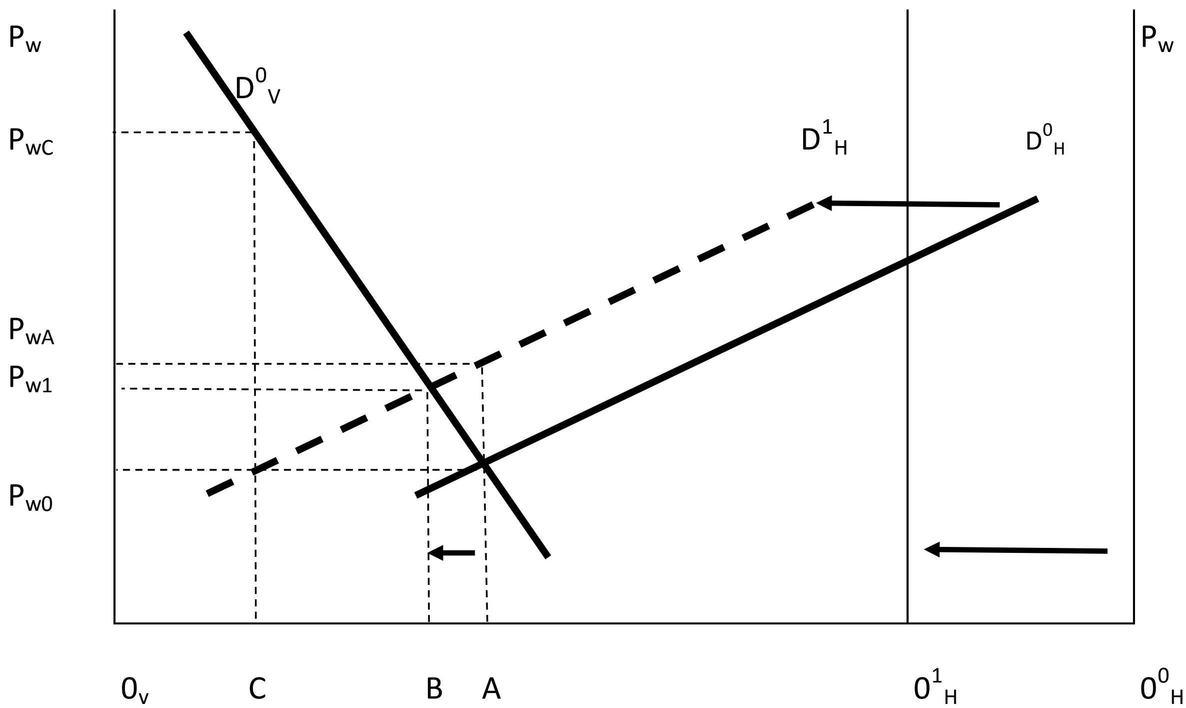
NOTE: The county boundary shapefile data come from the Minnesota Population Center. *National Historical Geographic Information System: Version 2.0*. Minneapolis, MN: University of Minnesota 2011. http://www.nhgis.org. The river shapefile data come from National Weather Service GIS—AWIPS Shapefile Database.

Figure 1b: Rivers in the Rio Grande River Valley Area



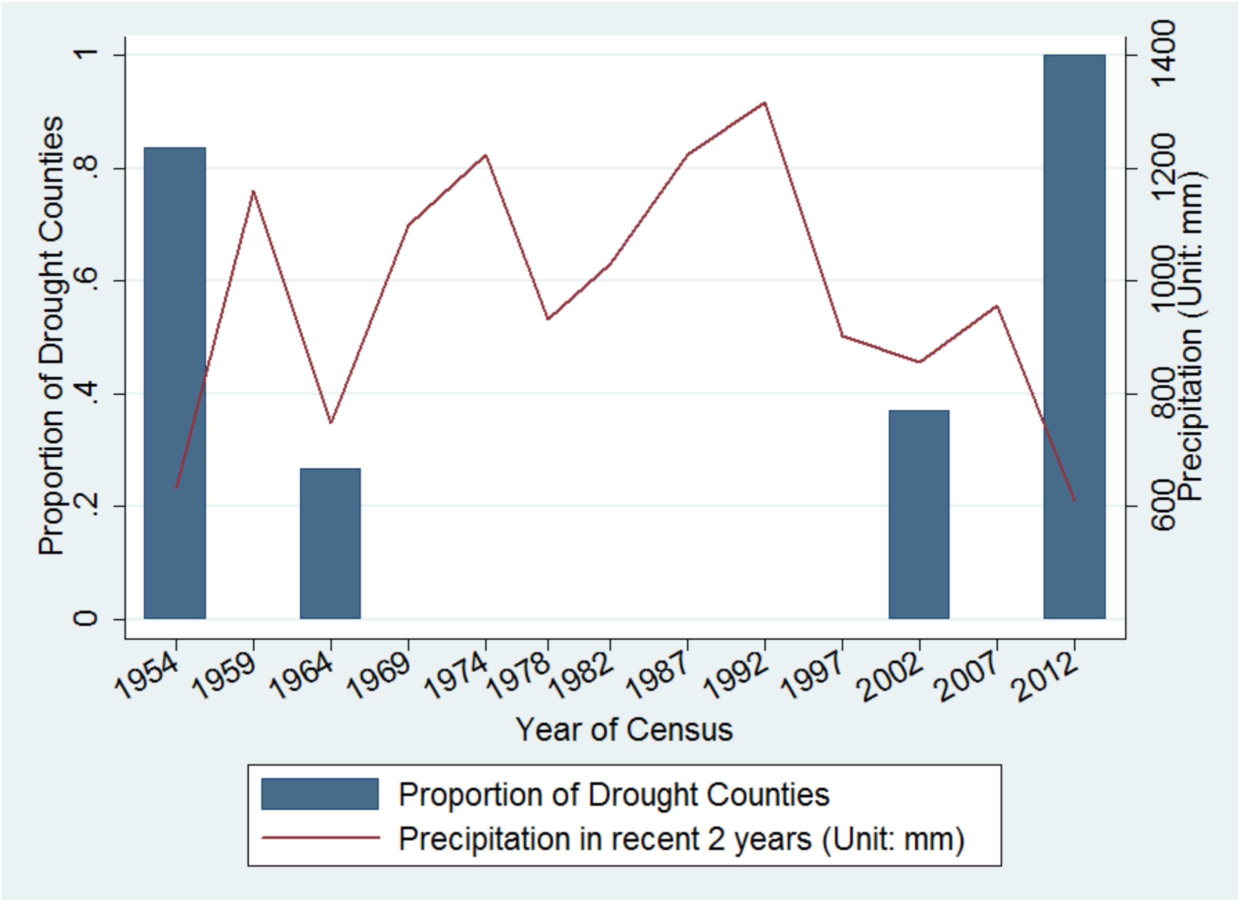
NOTE: The county boundary shapefile data come from the Minnesota Population Center. *National Historical Geographic Information System: Version 2.0*. Minneapolis, MN: University of Minnesota 2011. http://www.nhgis.org. The river shapefile data come from National Weather Service GIS—AWIPS Shapefile Database.

Figure 2: Reallocating Water with a Water Market in a Specific-Factors Model



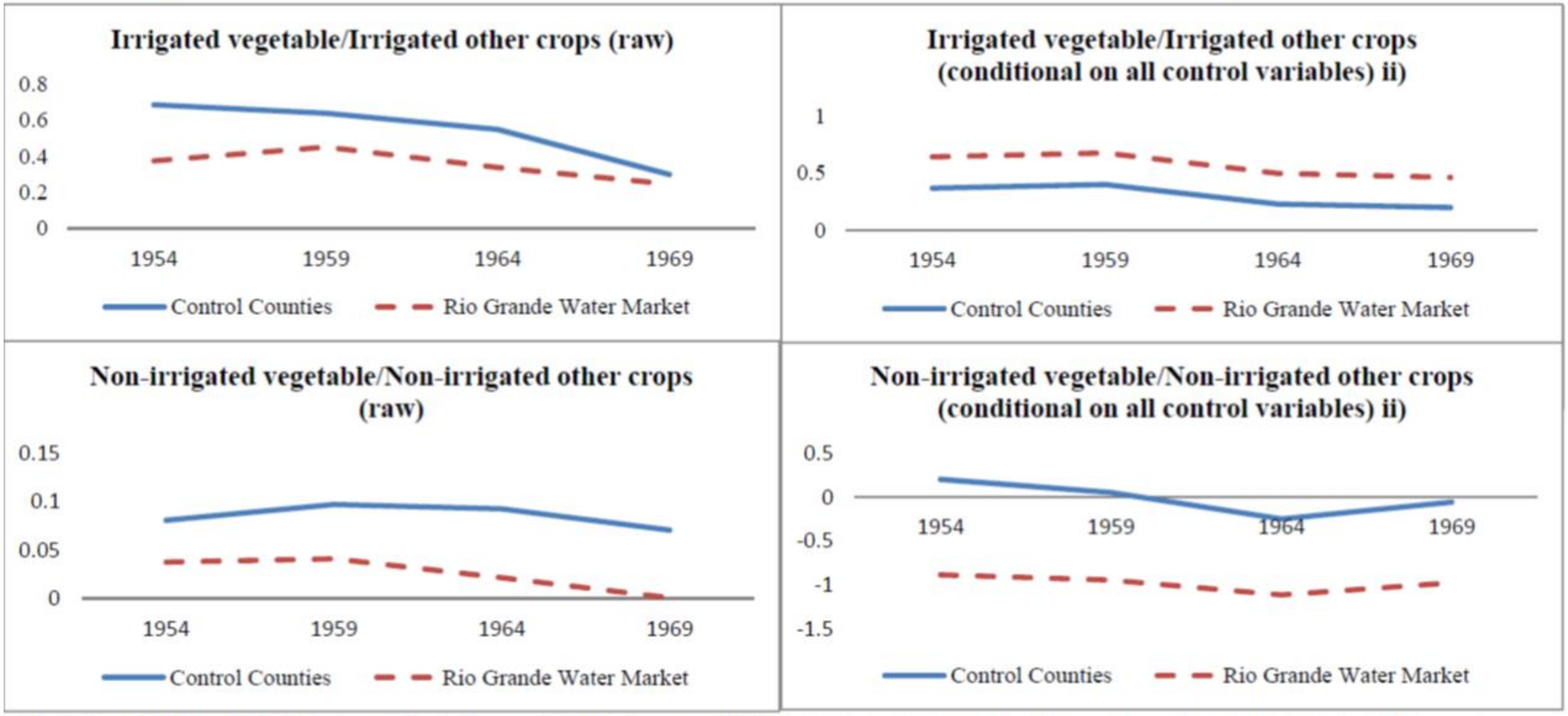
NOTE: D^0_v and D^0_H depict the initial demand for water (marginal-value product of water) for vegetable and hay—$D^0_{H's}$ has 0^0_H as its origin. D^1_H represents the demand for water when the total amount of water available in the region has shrunk from $0_v0^0_H$ to $0_v0^1_H$ (i.e., D^1_H shifts to the left with the same amount with which the outer-right y-axis shifts to the left). As one can see, the price of water rises from P_{w0} to P_{w1}, and water use in vegetables shrink with less (the difference between A and B) than does water use in hay (the leftward shift of the outer y-axis, $0^0_H0^1_H$). C shows how water is distributed between hay and vegetables after the water reduction when hay holds the most-senior rights—the entire water reduction is at the expense of vegetables, and the marginal-value product for vegetables (P_{Wc}) is higher than for hay (P_{w0}). When vegetables hold the most-senior rights, A shows how water is distributed after the water reduction: the value-marginal product of water is higher in hay (P_{wA}) than it is for vegetables (P_{w0}).

Figure 3: Drought/Precipitation in Rio Grande



NOTE: The average county-level precipitation in the last two years (the census year and the previous year) is reported for all the years of the census from 1954 to 2012 in millimeters and measured along the right-hand y-axis. Based on the precipitation data, we construct a measure of drought that equals 1 if the annual precipitation is smaller than the long-term (1954–2012) mean minus the long-term standard deviation for the entire period in the county. Otherwise, the drought measure equals 0. The vertical bars that are measured along the left axis indicate the fraction of the counties that experience a drought. As one can see, the 1970s, 1980s, and 1990s are especially the wetter years.

Figure 4: Pre-market Ratios for Higher and Lower Value Crops by Irrigated and Non-irrigated Areas

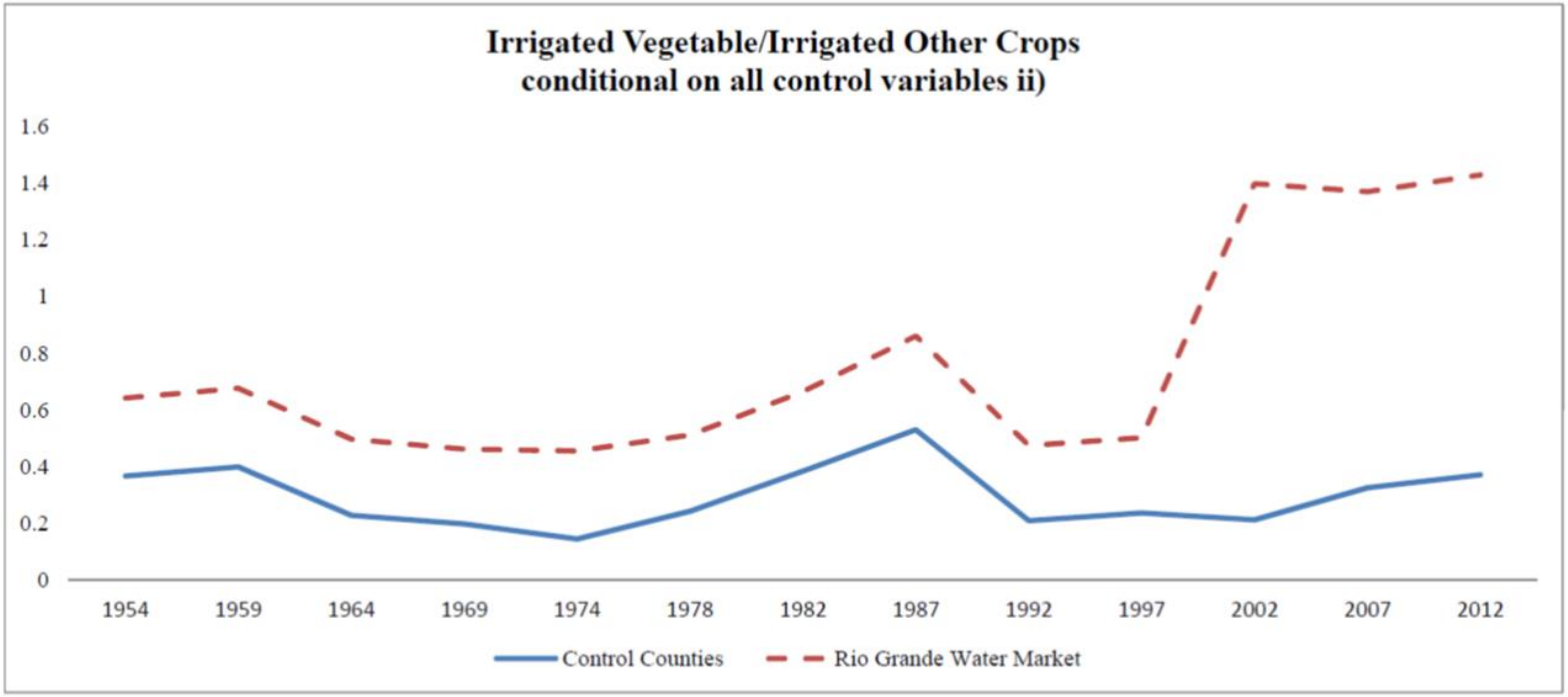


Note: i) Raw data from USDA Census of Agriculture and Population; precipitation data from the Center for Climate Research at the University of Delaware. by Willmott and Matsuura; temperature data collected by the United States Historical Climatology Network (USHCN).

ii) "Conditional on all control variables" means that residuals are reported after controlling the full set of control variables including precipitation, the degree-day counts, county-level logarithmic values of total farmland area, pasture area, and the per acre revenue from pasture, the values of the outcome variables in pre-market years interacted with year dummies, as well as county fixed-effect, year fixed-effect, crop fixed-effect, and crop x year dummies. Regressions are weighted by the county-level average harvest area for each crop in pre-market years.

iii) The two figures on the left show that the raw ratio of outcome variables by higher over lower value crops do not exhibit perfectly paralell pre-market trends for the treatment and control conties, but the residuals conditional on our full set of control variables exhibit paralell pre-market trends on the right.

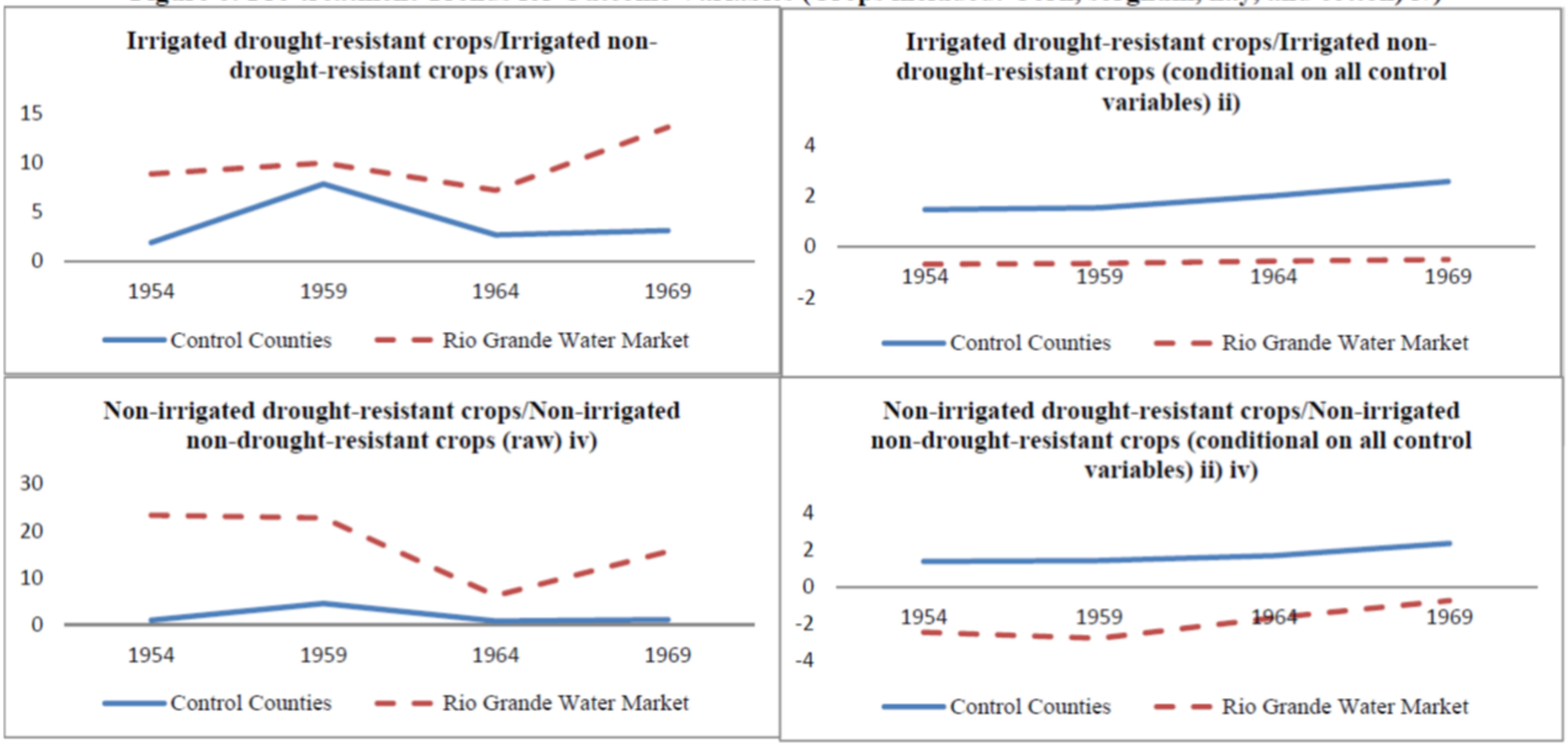
Figure 5: All Year Ratios for Higher and Lower Value Crops by Irrigated and Non-irrigated Areas Conditional on All Control Variables ii)



Note: i) Raw data from USDA Census of Agriculture and Population; precipitation data from the Center for Climate Research at the University of Delaware. by Willmott and Matsuura; temperature data collected by the United States Historical Climatology Network (USHCN).

ii) "Conditional on all control variables" means that residuals are reported after controlling the full set of control variables including precipitation, the degree-day counts, county-level logarithmic values of total farmland area, pasture area, and the per acre revenue from pasture, the values of the outcome variables in pre-market years interacted with year dummies, as well as county fixed-effect, year fixed-effect, crop fixed-effect, and crop x year dummies. Regressions are weighted by the county-level average harvest area for each crop in pre-market years.

Figure 6: Pre-treatment Trends for Outcome Variables (Crops included: Corn, sorghum, hay, and cotton) iv)



Note: i) Raw data from USDA Census of Agriculture and Population; precipitation data from the Center for Climate Research at the University of Delaware. by Willmott and Matsuura; temperature data collected by the United States Historical Climatology Network (USHCN).

ii) "Conditional on all control variables" means that residuals are reported after controlling the full set of control variables including precipitation, the degree-day counts, county-level logarithmic values of total farmland area, pasture area, the per acre revenue from pasture, harvest area of other crops, and revenue from other crops, the values of the outcome variables in pre-market years interacted with year dummies, as well as county fixed-effect, year fixed-effect, crop fixed-effect, and crop x year dummies. Regressions are weighted by the county-level average harvest area for each crop in pre-market years.

iii) The two figures on the left show that the raw averages of outcome variables do not exhibit perfectly paralell pre-market trends for the treatment and control conties, but the residuals conditional on our full set of control variables exhibit paralell pre-market trends as in the two figures on the right.

iv) Cotton is excluded for non-irrigated ratios due to a data issue in 1969. Similarly, wheat is excluded because data are missing in the 1950s.

Table 1: Water Rights in Rio Grande

water use	1,000 m^3	share (%)
domestic/municipal	459307	16
industry	61596	2
agriculture	2268327	80
mining	29028	1
Total	2818258	100

NOTE: Rio Grande Watermaster, http://www.tceq.state.tx.us/permitting/water_rights/wr-permitting/wr_databases.html.

Table 2: Total Acreage of Counties in the Region
(Number of Counties: 19)

Variables		Total acreage in 1964	Total acreage in 2012
Farmland area		14,706,300	13,337,032
Total cropland area		1,600,181	1,543,247
Irrigated land area		740,878	449,108
Corn	Non-irrigated area	3,723	38,997
	Irrigated area	6,393	38,783
Sorghum	Non-irrigated area	187,802	345,142
	Irrigated area	129,250	92,989
Wheat	Non-irrigated area	1,879	17,870
	Irrigated area	687	12,561
Vegetable	Non-irrigated area	20,074	16,605
	Irrigated area	147,199	43,407
Fruit	Non-irrigated area	4,602	5,402
	Irrigated area	60,919	21,496
Cotton	Non-irrigated area	173,794	67,674
	Irrigated area	214,141	69,334
Hay	Non-irrigated area	86,177	61,856
	Irrigated area	64,207	31,863

NOTE: *Census of Agriculture and Population*, 1964 & 2012.

Table 3: Real Water Productivity by years and crops (1969 baseline, \$/m^3)

	Categorical Measures			Measures for individual crops calculated from prices				
	Vegetables	Fruits	Other Crops	Corn	Sorghum	Wheat	Hays	Cotton
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1954	0.964	0.2595	0.2633	0.1679	0.3315	0.1263	0.1085	0.4813
1959	0.9779	0.366	0.3185	0.1985	0.3599	0.223	0.1117	0.5286
1964	1.412	0.462	0.2285	0.259	0.4423	0.2297	0.1863	0.446
1969	2.5108	0.2272	0.1938	0.3376	0.5683	0.2112	0.1659	0.279
1974	6.7892	0.7403	0.4034	0.7111	1.4727	0.7199	0.3219	0.5946
1978	5.119	0.6603	1.2885	0.894	4.0358	0.4855	0.3795	1.0128
1982	7.4578	1.6558	1.0589	1.2929	1.4219	0.6134	0.4595	1.1353
1987	8.3532	0.998	1.2237	0.9302	1.0954	0.498	0.4632	1.505
1992	8.6791	2.1292	1.4046	1.0885	1.382	0.6887	0.4502	1.04
1997	14.969	1.6891	1.2674	1.5658	1.7077	0.8812	0.5951	1.2785
2002	22.1212	1.9301	1.284	1.0686	1.3977	0.6044	0.6322	1.2119
2007	24.2517	4.2633	1.9409	2.6221	2.7383	1.0723	1.2896	2.3087
2012	24.5595	4.76	2.7215	4.097	4.5917	1.8442	0.971	2.6847

NOTE: Data constructed from USDA Census of Agriculture and Population (1954-2012), Brouwer and Heibloem (1986), and USDA Feed Grains Data: Yearbook Tables (2015). Market values of crops in Columns (1)-(3) are directly taken from the USDA Census, while those in Columns (4)-(8) are calculated from the price data in USDA Feed Grains Data (2015). Therefore, the numbers in Columns (1)-(3) are not comparable to the numbers in Columns (4) - (8).

Table 4: The Effect of Water Market on Irrigated Area/Total Farmland Area for Three Categories of Crops (Unit: %)
(Crop categories included in regressions: Vegetables, fruits, and other crops)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	-1.574	-1.807	-0.718	-1.130	-1.446	-0.728	-0.0451	-0.406	-0.113
	(1.683)	(1.788)	(0.634)	(1.986)	(2.100)	(0.710)	(2.058)	(2.139)	(0.576)
Post*WaterMarket				2.601***	2.737***	2.089**	1.764***	1.859**	1.343*
*Real Water Productivity ($/m^3) i)				(0.789)	(0.808)	(0.836)	(0.601)	(0.649)	(0.644)
Post*WaterMarket*Drought ii)							-7.954***	-7.407***	-1.842
							(2.395)	(2.212)	(1.108)
Post*WaterMarket*Drought							8.252**	8.252**	8.994***
*Real Water Productivity ($/m^3)							(2.979)	(3.033)	(2.764)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	588	582	574	588	582	574	588	582	574
R-squared	0.874	0.878	0.905	0.898	0.902	0.929	0.902	0.906	0.931

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Low RGV Counties*Real Water Productivity, Middle RGV Counties* *Real Water Productivity, and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Real water productivity and *Drougl Middle RGV Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, and per acre revenue from pasture.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1

Table 5: The Effect of Water Market on Non-irrigated Area/Total Farmland Area for Three Categories of Crops (Unit: %)
(Crop categories included in regressions: Vegetables, fruits, and other crops)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	3.756**	0.691	2.384	5.143**	1.852	2.682	4.637**	1.539	2.726*
	(1.659)	(1.790)	(1.439)	(1.870)	(1.766)	(1.695)	(1.643)	(1.703)	(1.505)
Post*WaterMarket				0.834	1.406*	1.951**	0.319	0.944	1.354*
*Real Water Productivity ($/m^3) i)				(0.700)	(0.750)	(0.751)	(0.648)	(0.678)	(0.709)
Post*WaterMarket*Drought ii)							7.021**	7.802***	1.496
							(2.475)	(2.522)	(1.958)
Post*WaterMarket*Drought							6.624**	5.856*	5.453*
*Real Water Productivity ($/m^3)							(3.006)	(3.014)	(3.099)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	581	575	567	581	575	567	581	575	567
R-squared	0.866	0.904	0.933	0.887	0.925	0.954	0.891	0.930	0.955

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Low RGV Counties*Real Water Productivity, Middle RGV Counties* *Real Water Productivity, and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Real water productivity and *Drougt Middle RGV Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, and per acre revenue from pasture.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1

Table 6: Counties Characteristics in Pre-market Years (1954-69)

		Water Market and Their		Water Market and the Extended	
		Pooled Mean and Std. Dev.	Differences	Pooled Mean and Std. Dev.	Differences
		(1)	(2)	(3)	(4)
Log(farmland area)		13.697	-0.345	13.734	-0.122
		(0.490)	(0.219)	(0.492)	(0.0893)
Log(pasture area)		13.592	-0.647**	13.662	-0.289**
		(0.687)	(0.284)	(0.644)	(0.141)
Log(per acre revenue from pasture)		1.408	0.356	1.315	0.160
		(0.760)	(0.340)	(0.711)	(0.186)
Log(harvest area of excluded crops) i)		7.618	0.826	7.175	0.547*
		(1.615)	(0.711)	(2.378)	(0.269)
Log(irrigated area of excluded crops) i)		5.060	1.960	4.410	0.812
		(3.182)	(1.362)	(3.112)	(0.727)
Log(revenue from excluded crops) i)		11.406	0.901	10.305	1.604**
		(3.357)	(1.235)	(4.288)	(0.634)
Corn for Grain	Non-irrigated area/farmland	0.064	0.0370	0.094	-0.0141
		(0.112)	(0.0327)	(0.297)	(0.0583)
	Irrigated area/farmland	0.096	0.138	0.061	0.104
		(0.243)	(0.131)	(0.197)	(0.0789)
Sorghum for Grain	Non-irrigated area/farmland	1.267	2.702*	1.260	1.291
		(3.518)	(1.500)	(3.286)	(0.926)
	Irrigated area/farmland	0.742	1.460	0.477	0.961
		(2.226)	(0.974)	(1.805)	(0.601)
Wheat	Non-irrigated area/farmland	0.023	0.0213	0.036	0.000883
		(0.055)	(0.0317)	(0.067)	(0.0194)
	Irrigated area/farmland	0.026	0.00831	0.019	-0.00911
		(0.066)	(0.0185)	(0.054)	(0.0105)
Vegetable	Non-irrigated area/farmland	0.170	0.124	0.161	0.151**
		(0.359)	(0.111)	(0.309)	(0.0685)
	Irrigated area/farmland	1.154	2.081	0.829	1.463*
		(2.475)	(1.308)	(2.155)	(0.859)
Fruit	Non-irrigated area/farmland	0.043	0.101	0.036	0.0511
		(0.133)	(0.0645)	(0.110)	(0.0444)
	Irrigated area/farmland	0.450	1.219	0.285	0.756
		(1.548)	(0.896)	(1.244)	(0.557)
Cotton	Non-irrigated area/farmland	1.224	3.059*	0.998	1.725*
		(3.820)	(1.519)	(3.183)	(0.958)
	Irrigated area/farmland	1.720	4.013*	1.142	2.664*
		(4.816)	(2.289)	(3.996)	(1.532)
All Hays	Non-irrigated area/farmland	0.404	0.207	0.515	-0.00807
		(0.669)	(0.217)	(0.829)	(0.137)
	Irrigated area/farmland	0.337	0.372	0.243	0.191
		(0.550)	(0.246)	(0.458)	(0.144)

Note: i) Excluded crops are those other than corn, sorghum, wheat, vegetables, fruits, cotton, and hay, and are only relevant for when we run regressions on disaggregate crops.

ii) Weighted by farmland area in pre-market years. Standard errors clustered at the county-level.

*** p<0.01, ** p<0.05, * p<0.1

Table 7: The Effect of Water Market on Irrigated Area/Total Farmland Area for 5 Crops (Unit: %)
(Crops included in regressions: Corn, sorghum, wheat, hay, and cotton)

	(1)	(2)	(3)	(4)	(5)	(6)
Post*WaterMarket	-0.301*	-0.431	-0.0313	-0.509*	-0.742	-0.479
	(0.170)	(0.375)	(0.746)	(0.275)	(0.559)	(0.944)
Post*WaterMarket	0.602	0.471	0.198	1.081	1.215	0.868
*Drought Resistant Crops i)	(0.793)	(0.975)	(0.965)	(1.123)	(1.259)	(1.273)
Post*WaterMarket*Drought ii)				0.686	1.335	2.437*
				(0.891)	(1.622)	(1.218)
Post*WaterMarket*Drought				-2.000	-2.774**	-3.005**
*Drought Resistant Crops				(1.247)	(1.292)	(1.082)
Other triple and double interactions iii)	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes
Observations	1,079	1,072	1,051	1,079	1,072	1,051
R-squared	0.851	0.865	0.898	0.852	0.867	0.900

NOTE: i) "Drought Resistant Crops" refers to sorghum and cotton, which are categorized as low drought sensitvity crops by FAO.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise

iii) For Columns (1)-(3), "Other triple and double interactions" include Low RGV Counties*Drought Resistant Crops and Middle RGV Counties*Drought Resistant Crops. Post*Drought Resistant Crops is absorbed by Item*Year Dummies. For Columns (4)-(6), "Other triple and double interactions" include Post*Drought, Drought*Drought Resistant Crops, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Drought Resistant Crops and *Drought, Middle RGV Counties*Drought and Post*Drought Resistant Crops*Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 8: The Effect of Water Market on Non-irrigated Area/Total Farmland Area for 5 Crops (Unit: %)
(Crops included in regressions: Corn, sorghum, wheat, hay, and cotton)

	(1)	(2)	(3)	(4)	(5)	(6)
Post*WaterMarket	-0.543*	-1.302*	-1.286**	-0.880*	-1.368*	-1.426**
	(0.280)	(0.706)	(0.602)	(0.448)	(0.685)	(0.538)
Post*WaterMarket	4.453***	3.245***	3.677***	3.606***	2.293**	2.899***
*Drought Resistant Crops i)	(1.198)	(1.094)	(0.969)	(0.970)	(0.936)	(0.750)
Post*WaterMarket*Drought ii)				2.182	1.642	0.895
				(1.334)	(1.458)	(1.486)
Post*WaterMarket*Drought				8.179***	9.425***	8.231***
*Drought Resistant Crops				(2.125)	(2.563)	(2.354)
Other triple and double interactions iii)	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes
Observations	1,060	1,053	1,033	1,060	1,053	1,033
R-squared	0.802	0.833	0.857	0.805	0.837	0.858

NOTE: i) "Drought Resistant Crops" refers to sorghum and cotton, which are categorized as low drought sensitvity crops by FAO.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise

iii) For Columns (1)-(3), "Other triple and double interactions" include Low RGV Counties*Drought Resistant Crops and Middle RGV Counties*Drought Resistant Crops. Post*Drought Resistant Crops is absorbed by Item*Year Dummies. For Columns (4)-(6), "Other triple and double interactions" include Post*Drought, Drought*Drought Resistant Crops, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Drought Resistant Crops and *Drought, Middle RGV Counties*Drought and Post*Drought Resistant Crops*Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 9: The Effect of Water Market on Irrigated Area/Total Farmland Area for Corn, Wheat, and Hay (Unit: %)
(Crops included in regressions: Corn, wheat, and hay)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	-0.253*	-0.249**	0.0142	-0.400**	-0.396**	-0.137	-0.306*	-0.314**	-0.0839
	(0.131)	(0.115)	(0.0566)	(0.161)	(0.144)	(0.0798)	(0.151)	(0.140)	(0.0759)
Post*WaterMarket				3.638**	3.672**	3.656**	2.641*	2.675*	2.600*
*Real Water Productivity ($/m^3) i)				(1.391)	(1.407)	(1.354)	(1.381)	(1.420)	(1.380)
Post*WaterMarket*Drought ii)							-0.409*	-0.343	-0.384
							(0.198)	(0.214)	(0.336)
Post*WaterMarket*Drought							13.55**	13.58**	12.88**
*Real Water Productivity ($/m^3)							(4.725)	(4.853)	(5.229)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	616	612	598	616	612	598	616	612	598
R-squared	0.687	0.690	0.727	0.734	0.737	0.773	0.755	0.757	0.791

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Low RGV Counties*Real Water Productivity, Middle RGV Counties* *Real Water Productivity, and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Real water productivity and *Drought, Middle RGV Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 1: The Effect of Water Market on Irrigated Area/Total Farmland Area for Three Categories of Crops (Unit: %) (Using the Expanded Control Group as in Figure 1; Crop categories included in regressions: Vegetables, fruits, and other crops)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	-2.071	-2.173	-0.257	-1.816	-1.947	-0.479	-0.657	-0.858	0.0184
	(1.381)	(1.329)	(0.668)	(1.545)	(1.491)	(0.716)	(1.453)	(1.439)	(0.627)
Post*WaterMarket				2.972***	3.067***	2.174**	2.091***	2.145***	1.428**
*Real Water Productivity ($/m^3) i)				(0.846)	(0.810)	(0.813)	(0.598)	(0.573)	(0.612)
Post*WaterMarket*Drought ii)							-6.794***	-6.047***	-0.866
							(1.779)	(1.625)	(1.005)
Post*WaterMarket*Drought							7.053**	7.178**	8.133***
*Real Water Productivity ($/m^3)							(2.591)	(2.658)	(2.367)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	883	868	860	883	868	860	883	868	860
R-squared	0.887	0.891	0.916	0.908	0.912	0.938	0.912	0.916	0.940

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Low RGV Counties*Real Water Productivity, Middle RGV Counties* *Real Water Productivity, and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Real water productivity and *Drought, Middle RGV Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, and per acre revenue from pasture.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1

Appendix Table 2: The Effect of Water Market on Non-irrigated Area/Total Farmland Area for 3 Categories of Crops (Unit: %) (Using the Expanded Control Group as in Figure 1; Crop categories included in regressions: Vegetables, fruits, and other crops)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	4.661**	2.437	3.350***	5.633***	3.337**	3.731**	5.441***	3.096**	3.739***
	(1.720)	(1.572)	(1.162)	(1.918)	(1.577)	(1.468)	(1.747)	(1.318)	(1.297)
Post*WaterMarket				0.398	0.611	1.489*	-0.0985	0.246	0.908
*Real Water Productivity ($/m^3) i)				(0.720)	(0.758)	(0.760)	(0.650)	(0.610)	(0.713)
Post*WaterMarket*Drought ii)							4.844	6.393**	1.005
							(2.923)	(2.386)	(1.577)
Post*WaterMarket*Drought							4.651	3.753	3.137
*Real Water Productivity ($/m^3)							(3.215)	(3.094)	(3.139)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	871	856	848	871	856	848	871	856	848
R-squared	0.863	0.898	0.930	0.881	0.917	0.948	0.885	0.923	0.950

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Low RGV Counties*Real Water Productivity, Middle RGV Counties* *Real Water Productivity, and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Real water productivity and *Drought, Middle RGV Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, and per acre revenue from pasture.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 3: The Effect of Water Market on Irrigated Area/Total Farmland Area for 5 Crops (Unit: %)
(Using the Expanded Control Group as in Figure 1; Crops included in regressions: Corn, sorghum, wheat, hay, and cotton)

	(1)	(2)	(3)	(4)	(5)	(6)
Post*WaterMarket	-0.515**	-0.467*	0.874	-0.686**	-0.673	0.362
	(0.216)	(0.266)	(0.542)	(0.331)	(0.483)	(0.722)
Post*WaterMarket	-0.254	0.0159	-0.406	0.392	0.735	0.333
*Drought Resistant Crops i)	(0.754)	(0.929)	(0.839)	(0.898)	(1.078)	(1.061)
Post*WaterMarket*Drought ii)				0.947	0.893	2.737***
				(0.876)	(1.073)	(0.984)
Post*WaterMarket*Drought				-2.791**	-2.705**	-3.240***
*Drought Resistant Crops				(1.190)	(1.017)	(1.002)
Other triple and double interactions iii)	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes
Observations	1,633	1,607	1,586	1,633	1,607	1,586
R-squared	0.855	0.864	0.896	0.856	0.866	0.898

NOTE: i) "Drought Resistant Crops" refers to sorghum and cotton, which are categorized as low drought sensitvity crops by FAO.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise

iii) For Columns (1)-(3), "Other triple and double interactions" include Low RGV Counties*Drought Resistant Crops and Middle RGV Counties*Drought Resistant Crops. Post*Drought Resistant Crops is absorbed by Item*Year Dummies. For Columns (4)-(6), "Other triple and double interactions" include Post*Drought, Drought*Drought Resistant Crops, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Drought Resistant Crops and *Drought, Middle RGV Counties*Drought and Post*Drought Resistant Crops*Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 4: The Effect of Water Market on Non-irrigated Area/Total Farmland Area for 5 Crops (Unit: %)
(Using the Expanded Control Group as in Figure 1; Crops included in regressions: Corn, sorghum, wheat, hay, and cotton)

	(1)	(2)	(3)	(4)	(5)	(6)
Post*WaterMarket	-0.381	-0.579	-0.0916	-0.811*	-1.026	-0.648
	(0.351)	(0.662)	(0.618)	(0.459)	(0.666)	(0.554)
Post*WaterMarket	3.853**	2.627*	3.924***	3.969***	2.672***	4.009***
*Drought Resistant Crops i)	(1.708)	(1.427)	(1.316)	(1.312)	(0.905)	(0.991)
Post*WaterMarket*Drought ii)				2.278	2.748*	3.290**
				(1.410)	(1.353)	(1.537)
Post*WaterMarket*Drought				1.751	2.351	2.777
*Drought Resistant Crops				(3.024)	(3.212)	(3.424)
Other triple and double interactions iii)	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes
Observations	1,602	1,578	1,558	1,602	1,578	1,558
R-squared	0.780	0.809	0.836	0.782	0.813	0.838

NOTE: i) "Drought Resistant Crops" refers to sorghum and cotton, which are categorized as low drought sensitvity crops by FAO.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise

iii) For Columns (1)-(3), "Other triple and double interactions" include Low RGV Counties*Drought Resistant Crops and Middle RGV Counties*Drought Resistant Crops. Post*Drought Resistant Crops is absorbed by Item*Year Dummies. For Columns (4)-(6), "Other triple and double interactions" include Post*Drought, Drought*Drought Resistant Crops, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Drought Resistant Crops and *Drought, Middle RGV Counties*Drought and Post*Drought Resistant Crops*Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 5: The Effect of Water Market on Irrigated Area/Total Farmland Area for Corn, Wheat, and Hay (Unit: %)
(Using the Expanded Control Group as in Figure 1; Crops included in regressions: Corn, wheat, and hay)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	-0.238**	-0.238**	0.0180	-0.435***	-0.435***	-0.157**	-0.346**	-0.346**	-0.0964
	(0.108)	(0.108)	(0.0395)	(0.151)	(0.151)	(0.0612)	(0.132)	(0.132)	(0.0573)
Post*WaterMarket				4.865***	4.865***	4.973***	3.887**	3.887**	4.069***
*Real Water Productivity ($/m^3) i)				(1.587)	(1.587)	(1.617)	(1.416)	(1.416)	(1.458)
Post*WaterMarket*Drought ii)							-0.383**	-0.383**	-0.544*
							(0.185)	(0.185)	(0.301)
Post*WaterMarket*Drought							13.54***	13.54***	13.08***
*Real Water Productivity ($/m^3)							(4.428)	(4.428)	(4.492)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	945	945	929	945	945	929	945	945	929
R-squared	0.669	0.669	0.697	0.735	0.735	0.762	0.764	0.764	0.790

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Low RGV Counties*Real Water Productivity, Middle RGV Counties* *Real Water Productivity, and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Low RGV Counties*Drought, Middle RGV Counties*Drought, Low RGV Counties*Real water productivity and *Drought, Middle RGV Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 6: The Effect of Water Market on Irrigated Area/Total Farmland Area for Three Categories of Crops (Unit: %)
(Post period since 1971 for all 10 counties; Crop categories included in regressions: Vegetables, fruits, and other crops)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	-2.771	-3.182*	-0.228	-2.584	-2.992	-0.212	-1.326	-1.847	0.648
	(1.617)	(1.694)	(0.732)	(1.781)	(1.865)	(0.765)	(1.839)	(1.914)	(0.682)
Post*WaterMarket				3.861***	3.867***	3.981***	2.151**	2.115**	2.092**
*Real Water Productivity ($/m^3) i)				(1.196)	(1.150)	(1.180)	(0.764)	(0.765)	(0.816)
Post*WaterMarket*Drought ii)							-6.623***	-5.940***	-2.358**
							(1.900)	(1.636)	(0.946)
Post*WaterMarket*Drought							8.176**	8.315**	8.724***
*Real Water Productivity ($/m^3)							(2.858)	(2.976)	(2.584)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	588	582	574	588	582	574	588	582	574
R-squared	0.875	0.879	0.905	0.889	0.893	0.919	0.892	0.896	0.921

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Water Market Counties*Real Water Productivity and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Water Market Counties*Drought, Water Market Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, and per acre revenue from pasture.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 7: The Effect of Water Market on Non-irrigated Area/Total Farmland Area for 3 Categories of Crops (Unit: %)
(Post period since 1971 for all 10 counties; Crop categories included in regressions: Vegetables, fruits, and other crops)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	5.105***	2.297	3.383**	6.145***	3.140*	4.058***	5.805***	2.923*	4.404***
	(1.570)	(1.653)	(1.357)	(1.732)	(1.620)	(1.378)	(1.612)	(1.606)	(1.088)
Post*WaterMarket				1.145	2.006*	1.818	-0.863	0.0730	0.00828
*Real Water Productivity ($/m^3) i)				(0.892)	(1.090)	(1.057)	(0.792)	(0.518)	(0.558)
Post*WaterMarket*Drought ii)							5.700**	6.265**	0.392
							(2.470)	(2.763)	(1.999)
Post*WaterMarket*Drought							8.416**	7.474**	7.606**
*Real Water Productivity ($/m^3)							(3.251)	(3.085)	(3.240)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	581	575	567	581	575	567	581	575	567
R-squared	0.867	0.905	0.933	0.879	0.916	0.944	0.882	0.921	0.946

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Water Market Counties*Real Water Productivity and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Water Market Counties*Drought, Water Market Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, and per acre revenue from pasture.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** p<0.01, ** p<0.05, * p<0.1

Appendix Table 8: The Effect of Water Market on Irrigated Area/Total Farmland Area for 5 Crops (Unit: %)
(Post period since 1971 for all 10 counties; Crops included in regressions: Corn, sorghum, wheat, hay, and cotton)

	(1)	(2)	(3)	(4)	(5)	(6)
Post*WaterMarket	-0.350	-0.797	0.541	-0.632	-1.242	0.0347
	(0.204)	(0.519)	(0.566)	(0.387)	(0.734)	(0.740)
Post*WaterMarket	0.357	0.409	-0.0373	0.975	1.359	0.790
*Drought Resistant Crops i)	(0.660)	(0.902)	(0.891)	(1.079)	(1.264)	(1.231)
Post*WaterMarket*Drought ii)				0.920	1.920	2.042
				(0.978)	(1.640)	(1.390)
Post*WaterMarket*Drought				-2.048*	-3.104**	-3.035***
*Drought Resistant Crops				(1.181)	(1.176)	(0.998)
Other triple and double interactions iii)	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes
Observations	1,079	1,072	1,051	1,079	1,072	1,051
R-squared	0.839	0.853	0.886	0.841	0.855	0.888

NOTE: i) "Drought Resistant Crops" refers to sorghum and cotton, which are categorized as low drought sensitvity crops by FAO.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise

iii) For Columns (1)-(3), "Other triple and double interactions" include Water Market Counties*Drought Resistant Crops. Post*Drought Resistant Crops is absorbed by Item*Year Dummies. For Columns (4)-(6), "Other triple and double interactions" include Post*Drought, Drought*Drought Resistant Crops, Water Market Counties*Drought, Water Market Counties*Drought Resistant Crops and *Drought, and Post*Drought Resistant Crops*Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 9: The Effect of Water Market on Non-irrigated Area/Total Farmland Area for 5 Crops (Unit: %)
(Post period since 1971 for all 10 counties; Crops included in regressions: Corn, sorghum, wheat, hay, and cotton)

	(1)	(2)	(3)	(4)	(5)	(6)
Post*WaterMarket	-0.511*	-0.925	-1.321*	-1.002*	-1.121	-1.482*
	(0.247)	(0.768)	(0.688)	(0.526)	(0.806)	(0.725)
Post*WaterMarket	5.175***	3.683***	4.461***	4.462***	2.777**	3.730***
*Drought Resistant Crops i)	(1.167)	(1.129)	(0.978)	(1.012)	(0.979)	(0.725)
Post*WaterMarket*Drought ii)				2.425	1.472	1.488
				(1.506)	(1.468)	(1.787)
Post*WaterMarket*Drought				7.147***	8.834***	7.379***
*Drought Resistant Crops				(2.223)	(2.600)	(2.380)
Other triple and double interactions iii)	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes
Observations	1,060	1,053	1,033	1,060	1,053	1,033
R-squared	0.797	0.829	0.852	0.800	0.831	0.854

NOTE: i) "Drought Resistant Crops" refers to sorghum and cotton, which are categorized as low drought sensitvity crops by FAO.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise

iii) For Columns (1)-(3), "Other triple and double interactions" include Water Market Counties*Drought Resistant Crops. Post*Drought Resistant Crops is absorbed by Item*Year Dummies. For Columns (4)-(6), "Other triple and double interactions" include Post*Drought, Drought*Drought Resistant Crops, Water Market Counties*Drought, Water Market Counties*Drought Resistant Crops and *Drought, and Post*Drought Resistant Crops*Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 10: The Effect of Water Market on Irrigated Area/Total Farmland Area for Corn, Wheat, and Hay (Unit: %)
(Post period since 1971 for all 10 counties; Crop categories included in regressions: Corn, wheat, and hay)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post*WaterMarket	-0.216*	-0.220*	0.0236	-0.418**	-0.422**	-0.169*	-0.315**	-0.328**	-0.107
	(0.115)	(0.109)	(0.0640)	(0.158)	(0.148)	(0.0970)	(0.147)	(0.144)	(0.0990)
Post*WaterMarket				6.072***	6.101***	5.751***	5.096**	5.104**	4.850**
*Real Water Productivity ($/m^3) i)				(1.816)	(1.833)	(1.825)	(1.777)	(1.786)	(1.712)
Post*WaterMarket*Drought ii)							-0.403*	-0.352	-0.360
							(0.216)	(0.235)	(0.337)
Post*WaterMarket*Drought							9.972**	10.20*	10.03*
*Real Water Productivity ($/m^3)							(4.740)	(4.923)	(5.260)
Other triple and double interactions iii)	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item-fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item*Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Control Variables iv)	-	Yes	Yes	-	Yes	Yes	-	Yes	Yes
Pre-water-market Controls v)	-	-	Yes	-	-	Yes	-	-	Yes
Observations	616	612	598	616	612	598	616	612	598
R-squared	0.684	0.687	0.727	0.713	0.716	0.755	0.727	0.730	0.768

NOTE: i) Real water productivity is relative to the category with lowest level for each year.

ii) "Drought" equals to one if the precipitation in recent two years is less than long-term mean minus long-term standard deviation, and equals to zero otherwise.

iii) For Columns (4)-(6), "Other triple and double interactions" includes Water Market Counties*Real Water Productivity and Post*Real Water Productivity. For Columns (7)-(9), "Other triple and double interactions" includes Post*Drought, Drought*Real Water Productivity, Water Market Counties*Drought, Water Market Counties*Real water productivity and *Drought, Post*Real water productivity and *Drought. Other interaction terms are absorbed by fixed effects controlled.

iv) Other control variables include the logarithmic values of farmland area, pasture area, per acre revenue from pasture, harvest area of other crops, and revenue from other crops.

v) Pre-water-market Controls is the outcome variables in 1954 - 69 before the water market implemented interacted with dummies for the post-market years.

vi) Weighted by average county-level harvest areas in pre-market years by crops. Standard errors clustered at the county-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix Table 11: FAO-IIASA Agro-Climatic/Ecological Suitability Measures for Treated and Control Counties

		Rio Grande Water Market Counties (10 counties)		Neighboring Counties (9 counties)		Difference from Market Counties	Expanded Control Counties (19 counties)		Difference from Market Counties
	Crops	Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	
Agro-Climatic Potential Yields (Rainfed)	Maize	2490.791	566.8518	2483.648	575.7671	7.14	2430.823	902.5088	59.97
	Sorghum	3309.05	349.1832	3277.529	384.619	31.52	3169.792	789.1355	139.26
	Wheat	1528.207	68.40839	1568.561	365.3842	-40.35	1468.377	494.427	59.83
	Cabbage	1510.504	66.0118	1658.49	226.57	-147.99 *	1627.678	451.0473	-117.17
	Citrus	3.752094	14.90371	22.68208	62.31044	-18.93	353.1924	791.2475	-349.44 *
	Alfalfa	1.295243	5.144841	8.666908	19.94345	-7.37	97.18903	212.2248	-95.89 *
	Cotton	444.8896	42.14802	443.4013	39.11035	1.49	428.8117	87.25336	16.08
Agro-Ecological Suitability Values (Rainfed)	Maize	2,532.20	785.43	2,252.43	994.35	279.77	2,033.75	1,050.08	498.46
	Sorghum	3,891.65	1,932.02	3,428.44	1,641.03	463.21	3,227.27	1,856.18	664.38
	Wheat	2,443.09	607.73	2,245.23	726.57	197.86	2,048.82	927.19	394.27
	Cabbage	2,441.48	607.14	2,228.85	697.22	212.63	1,974.72	776.66	466.76 *
	Citrus	3.75	14.90	26.88	70.58	-23.13	385.96	986.97	-382.21
	Alfalfa	5.05	20.07	35.74	77.22	-30.69	384.53	989.37	-379.47
	Cotton	3,585.81	1,493.37	3,065.76	1,557.57	520.05	2,666.02	1,528.69	919.79
Agro-Ecological Suitability Values (Gravity Irrigated)	Maize	4,482.94	2,216.01	3,292.81	2,940.25	1,190.12	3,240.10	2,523.70	1,242.84
	Sorghum	4,735.61	2,485.11	3,299.41	2,936.92	1,436.20	3,243.26	2,522.02	1,492.35
	Wheat	3,552.11	1,643.89	2,521.13	2,006.88	1,030.98	2,651.67	1,723.78	900.45
	Cabbage	3,248.53	1,403.99	2,494.72	2,032.62	753.82	2,628.75	1,732.72	619.78
	Citrus	1,826.50	2,495.16	1,849.57	2,740.43	-23.07	2,517.82	2,505.81	-691.32
	Alfalfa	4,118.41	2,573.28	3,081.36	2,944.61	1,037.05	3,138.74	2,526.08	979.67
	Cotton	4,616.54	2,354.01	3,292.81	2,940.25	1,323.72	3,240.10	2,523.70	1,376.44

NOTE: Weighted by farmland area in pre-market years. * $p<0.1$

Source: Global Agro-Ecological Zones database by the Food and Agriculture Organization of the United Nations and the International Institute of Applied Systems Analysis. See http://gaez.fao.org/Main.html#.