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LOS BENEFICIOS POTENCIALES DE LA RE-ASIGNACÍON DEL AGUA ENTRE USUARIOS AGRÍCOLAS

THE POTENTIAL BENEFITS OF WATER REALLOCATION AMONG AGRICULTURAL USERS

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ABSTRACT

Irrigated fields produce a large share of the world's crops, but in many river basins agriculture faces growing competition from other water users. This paper focuses on the intensity of irrigation water use, i.e., the volume of water applied per unit of irrigated land, in the ten irrigation districts located on the Mexican side of the Rio Grande-Bravo Basin. Based on the analysis of historical production data for the districts' main crops, results show that irrigation intensity varies widely among the districts and through time. Local environmental conditions (aridity and seasonal availability of water) explain most of this variability; however, district-level organizational characteristics (plot sizes and the land tenure regime) also play a role. These features of agricultural water use within the water-stressed river basin point to substantial opportunities for using water transfers to meet non-agricultural water needs (including environmental uses) without affecting overall crop production.

Keywords: crop production, irrigation, water uses, environment, Rio Grande-Bravo Basin, Mexico.

RESUMEN

La agricultura de riego aporta gran parte de la producción global de cultivos, pero en muchas cuencas hidrográficas enfrenta una creciente competencia por parte de otros usuarios del agua. Este trabajo se enfoca en la intensidad del uso del agua de riego, es decir, el volumen de agua aplicado por unidad de tierra de regadío, en los diez distritos de riego ubicados en la parte Mexicana de la cuenca del Río Grande-Bravo. Con base en el análisis de datos históricos de producción para los principales cultivos de los distritos, los resultados muestran que la intensidad del riego varía ampliamente entre los distritos y a través del tiempo. Las condiciones ambientales locales (aridez y disponibilidad estacional del agua) explican buena parte de esta variabilidad, sin embargo las características organizacionales de los distritos (tamaño de las parcelas y régimen de tenencia de la tierra) también inciden. Estas características del uso agrícola del agua revelan oportunidades sustanciales para satisfacer las necesidades no agrícolas del agua (incluyendo los usos ambientales) sin afectar la producción agregada de cultivos en la cuenca, mediante transferencias de agua.

Palabras claves: *producción de cultivos, riego, usos del agua, medio ambiente, Cuenca del Río Grande-Bravo, México.*

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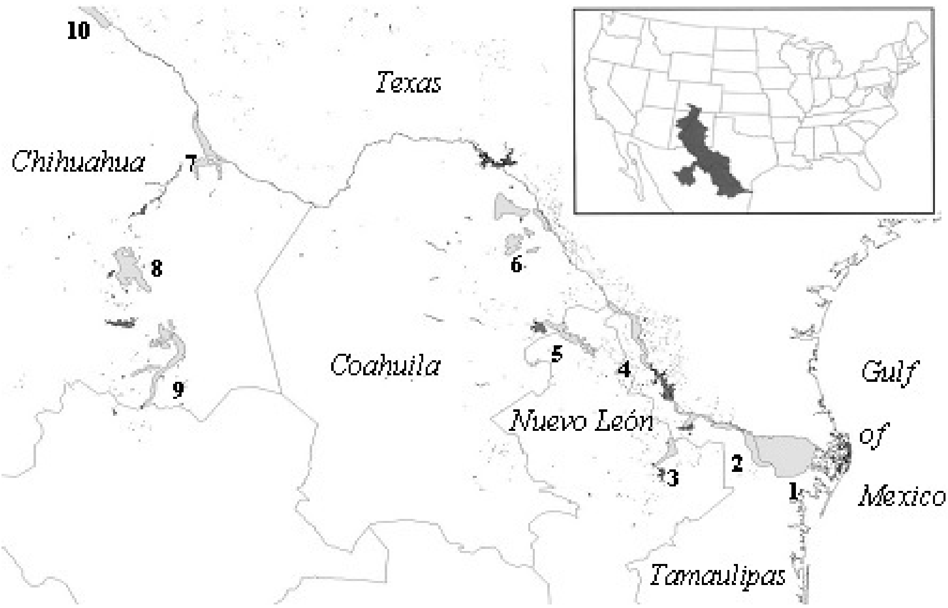
1. INTRODUCTION

Irrigated agriculture produces 40 percent of total agricultural output using only 20 percent of the world's cropped area (FAO,2016) -however it accounts for 70 percent of global freshwater use and faces growing competition from other users (UN-Water, 2014). This paper focuses on a fundamental component of agricultural water use: the volume of water applied per unit of irrigated land, hereafter irrigation intensity.

A long-standing experimental literature deals with optimal crop irrigation, for example Yaron (1967), Hexem and Heady (1978) and Steduto et al. (2012). Factors that motivate irrigators' adoption of water-saving application technologies have also been studied, for example Green et al. (1996).This paper addresses a different issue: given the crops they grow and the irrigation technologies they use, how much water do irrigators actually apply to their land? In particular, how does irrigation intensity relate to local environmental conditions (e.g. climate) as well as district-level organizational features (e.g. plot sizes)?To answer these questions, the paper offers an analysis of a dataset of surfaces irrigated and volumes of water applied over a period of ten years for the three main crops (corn, cotton and sorghum) grown in the ten irrigation districts that operate in the Mexican portion of the Rio Grande-Bravo Basin (MRGB). The information used to build this dataset comes from various editions of an annual report produced by Mexico's federal water authority (listed as Comisión Nacional del Agua-c in the references). Although in the public domain, this report is only available in print and not published or widely circulated - the authors obtained photocopies of said reports in person from the water authority's regional office in Monterrey, Nuevo León.

Figure 1. Rio Grande-Bravo Basin and MRGB Irrigation Districts.



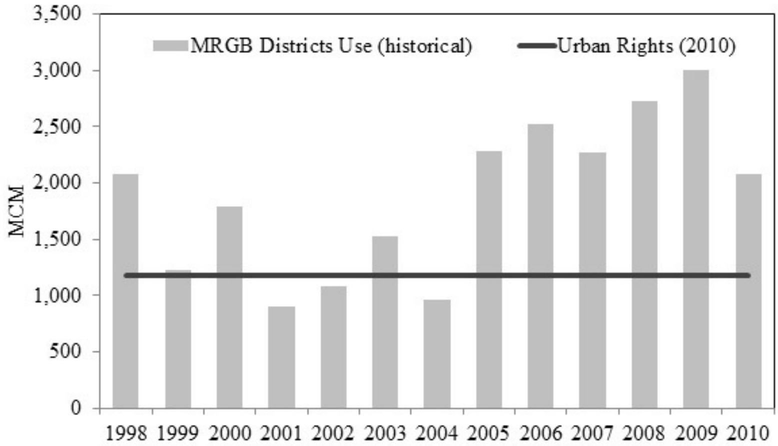
Source: Authors'.

†Key: **1**: ID025 Bajo Río Bravo; **2**: ID026 Bajo Río San Juan; **3**: ID031 Las Lajas; **4**: ID050 Acuña-Falcón; **5**: ID004 Don Martín; **6**: ID006 Palestina; **7**: ID090 Bajo Río Conchos; **8**: ID005 Delicias; **9**: ID103 Río Florido; **10**: ID009 Valle de Juárez.

The Rio Grande-Bravo Basin drains half a million square kilometers of land in the United States and Mexico. On the Mexican side of the basin (MRGB) consumptive uses capture more than three quarters of available water and for well over a decade the federal water authority has classified the region as highly water-stressed (Comisión Nacional del Agua-a, 2011, p.55). Ten irrigation districts - widely distributed at different elevations along the south bank of the Rio Grande-Bravo as well as the river's three main southern tributaries - operate in the MRGB (Figure 1).

The ten districts account for a significant share of water use in the MRGB. Figure 2 compares the volume of water supplied to the districts from 1998 to 2010 with the volume allocated to the region's municipal water authorities in 2010 - in Mexico water is national property and the federal water authority regulates and administers its use through a system of water rights. Although relatively large, the districts' water consumption varies markedly from year to year. This reflects the districts' dependence on surface water sources which are highly sensitive to the region's variable precipitation regime - surface water accounted for 97% of the districts' cumulative supply between 1998 and 2010.

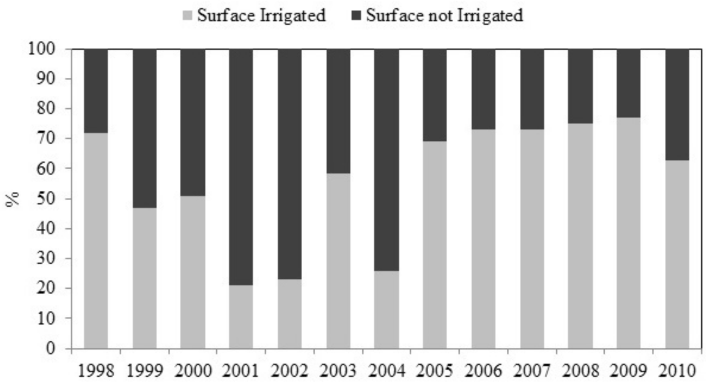
Figure 2. Yearly volume supplied to MRGB districts (1998-2010) vs. 2010 urban water rights (millions of cubic meters, MCM).



Source: Authors', with data from Comisión Nacional del Agua-a (2011) and Comisión Nacional del Agua-b (1998,…,2011).

The districts face a systematic shortage of water in the sense that even in years of relatively high water availability only a fraction of their combined irrigable surface of 458,000 hectares receives water (Figure 3). Water scarcity may turn acute in dry years for some districts, especially those located in the lower basin: for example, for two consecutive years (2001 and 2002) there was no irrigation at all in District 025 Bajo Río Bravo, the largest of the MRGB districts.

Figure 3. Surfaces irrigated and not irrigated, MRGB irrigation districts, 1998-2010 (% of total irrigable surface)



Source: Authors', with data from Comisión Nacional del Agua-b (1998,…, 2011).

This paper pursues two main objectives: 1) To quantify differences in irrigation intensity among the ten MRBG irrigation districts through time; 2) To assess the relationship between irrigation intensity and local environmental conditions as well as district-level organizational features. The rest of the paper is organized as follows. Section 2 defines our measure of irrigation intensity, describes the dataset and introduces the statistical model and methods employed in the following section; Section 3 presents and discusses the results; finally, Section 4 concludes.

2. DATA AND METHODS

For a given irrigation district, let W^{Gross} represent the total volume extracted from water sources for irrigation purposes; W^{Loss}, water lost in conveyance between water sources and the district; W^{Net}, water available for distribution to the irrigation modules; L, the total surface of land irrigated. The following water balance establishes our measure of water use intensity in the district, the ratio W^{Net} to L – hereafter *Net Irrigation Intensity* (*NII*):

$$(1)\quad W^{Gross} \equiv W^{Loss} + W^{Net} \equiv W^{Loss} + L \cdot \left(\frac{W^{Net}}{L}\right) \equiv W^{Loss} + L \cdot NII$$

The dataset consists of 216 observations. Each observation reports the net volume of water (in thousands of cubic meters) applied to crop "*i*" during growing season "*s*" of year "*t*" in irrigation district "*j*" (hereafter:w_{istj}) as well as the corresponding surface of land irrigated (in hectares, hereafter:l_{istj}).Referring to Equation (1), from these two quantities we compute:

$$(2)\quad NII_{istj} = \frac{w_{istj}}{l_{istj}} \cdot 10$$

Where the factor "10" scales *NII* in centimeters (cm). These data include the MRGB irrigation districts' three main crops: corn, cotton and sorghum - these accounted for 80% of the cumulative volume of water applied in all of the districts during the 10-year period of observation. The dataset contains all irrigation events recorded over that period.

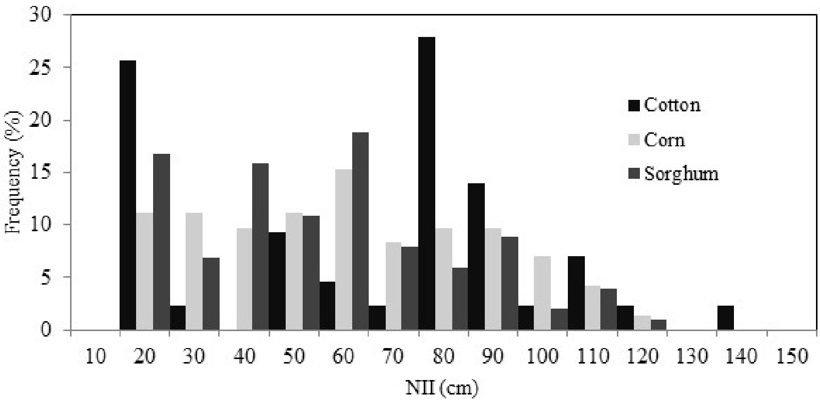
There are three growing seasons in the region: fall-winter, spring-summer and late summer. Over the period of observation most irrigation events (185 out of 216) occurred during the spring-summer season. Table 1 presents the basic summary statistics for *NII* by crop. Cotton (sorghum) tends to receive heavier (lighter) irrigation than corn but the differences are numerically small. For all three crops *NII* values show a wide range of values (Figure 4).

Table 1. Net Irrigation Intensity (*NII*) summary statistics, by crop.

	Corn	Cotton	Sorghum
Minimum (cm)	12.75	11.21	10.14
Average (cm)	56.59	60.15	51.37
Maximum (cm)	159.85	132.17	192.18
Standard Deviation	29.8	34.0	29.4
Number of observations	72	43	101

Source: Authors'.

Figure 4. *NII* frequency distribution, by crop.



Source: Authors'.

Local environmental conditions vary greatly within the MRGB. Table 2 presents for each irrigation district: geographical location (latitude and longitude); elevation (in meters above sea level, m.a.s.l.); average long term precipitation (in millimeters per year, mm/yr), evaporation (in mm/yr) and net evaporation (the difference between evaporation and precipitation, hereafter: aridity).These data show a clear pattern: as we move west (i.e. upstream, from the lower basin near the Gulf of Mexico coast), precipitation decreases, evaporation increases and the climate becomes more arid. Correlations between location and climate confirm this pattern (Table 3).

Table 2.Geographical location and climate, MRGB irrigation districts.

District	Latitude	Longitude	Elevation (m.a.s.l.)†	Precipitation (mm/year)	Evaporation (mm/year)	Aridity (mm/year)
ID025	26.00	98.50	20	672	1,823	1,151
ID026	26.23	98.60	80	584	2,083	1,499
ID031	25.78	99.18	123	550	2,317	1,767
ID050	27.48	99.73	180	450	2,450	2,000
ID004	27.00	100.62	240	410	2,365	1,955
ID006	29.15	100.98	332	517	2,446	1,929
ID090	29.57	104.40	841	217	2,673	2,456
ID005	28.18	105.47	1165	336	2,778	2,442
ID103	26.23	105.02	1367	383	2,316	1,933
ID009	31.35	105.98	1150	251	2,639	2,388

† Meters above sea level. Source: Authors'.

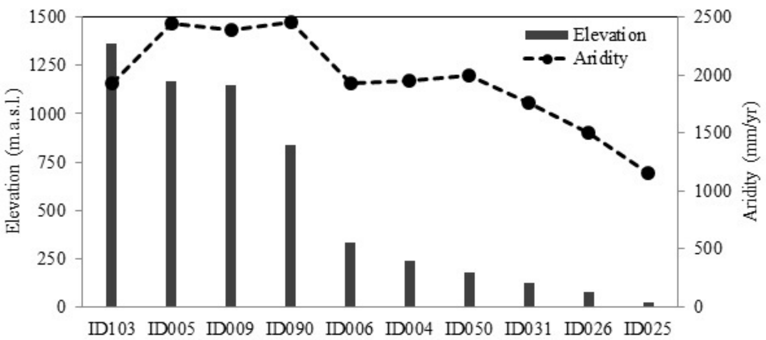
Table 3. Geographical location and climate, correlation matrix.

	Latitude	Longitude	Elevation	Precipitation	Evaporation	Aridity
Latitude	1					
Longitude	0.65	1				
Elevation	0.49	0.97	1			
Precipitation	-0.72	-0.88	-0.78	1		
Evaporation	0.72	0.76	0.64	-0.87	1	
Aridity	0.74	0.82	0.71	-0.94	0.98	1

Source: Authors'.

Moving upstream in the basin also means gaining elevation. Figure 5 illustrates the positive relationship for the basin's districts between elevation above sea level and aridity, making the former a potentially useful proxy for local environmental conditions.

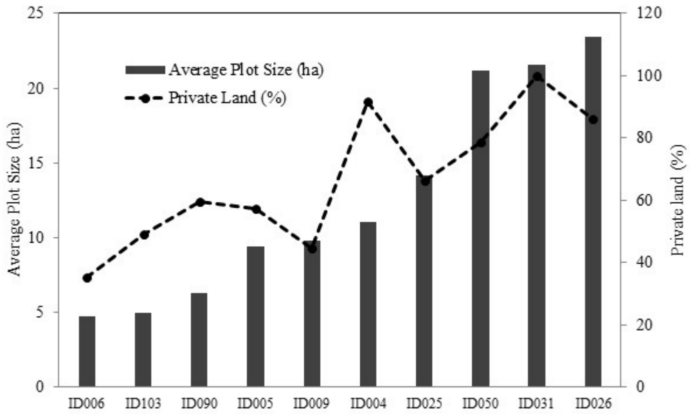
Figure 5. Elevation above sea level (meters) and aridity (mm/yr), MRGB irrigation districts.



Source: Authors'.

The MRGB irrigation districts also differ in terms of their organizational characteristics. Figure 6 presents for each district the average size of irrigators' plots, which we obtain by dividing the total surface of land irrigated during a year by the number of individual irrigators who received water during that year. Figure 6 also reports the percentage of land held privately - the remainder corresponds to communal land. Average irrigation plot size varies between districts from less than five to more than 20 hectares and it appears that the more prevalent private land tenure, the larger the plots. Note that these data (which are for 2005) in any given district may change to a limited extent through time.

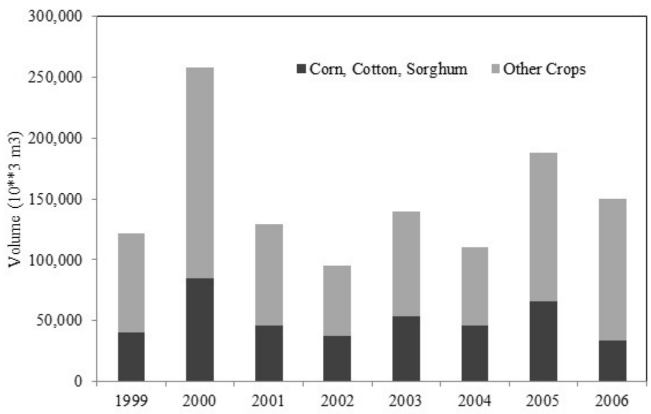
Figure 6. Average lot size and land tenure regime (percentage of private ownership), MRGB irrigation districts (2005).



Source: Authors'.

Water available for irrigation varies markedly in all districts from year to year, depending on rains, surface flows and stored volumes in reservoirs. The total volume of water applied in District 005 (Delicias) for the spring-summer season over a number of years illustrates this point (Figure 7). Water being scarce for the MRGB districts, we can assume that irrigators use all available water in any given season. We therefore measure seasonal availability in a given district as the net volume of water applied to all crops (not just corn, cotton and sorghum).

Figure 7. Water availability and volume applied by crop, spring-summer season, District 005.



Source: Authors'.

In the following section, we run two sets of regressions on the following model:

$$(3) \quad NII_{istj} = f\left(\{x_k\};\{\beta_k\}\right) + e_{istj}$$

Where x_k identifies an explanatory variable, β_k is a parameter to be estimated and e_{istj} represents a residual term. Each set of regressions includes a specific list of explanatory variables. In the first set explanatory variables refer to the districts' location and in the second, their environmental and organizational characteristics. We run the regressions on the whole dataset (all three crops together) as well as separately for each crop. Finally, to assess the robustness of the results we re-run the Ordinary Least-Squares (OLS) regressions on various alternative functional forms of Equation (3), diagnose extensively the residuals and re-estimate using a number of alternate regression techniques: OLS using a heteroscedasticity-consistent covariance matrix (HCC); Least Absolute Error (LAE); and, Maximum Likelihood (ML).

3. RESULTS AND DISCUSSION

This first set of regressions includes as independent variables nine dichotomous district identifiers (ID004,…,ID103), with value "1" for an irrigation event recorded in a given district and "0" for all other events (the reference district is ID005)or alternatively, each district's geographical location: latitude (Lat_j) and longitude ($Long_j$). The numerical values of district coefficients differ notably (Table 4). These differences show a clear spatial structure. Location matters, especially in terms of longitude: the more westerly a district's location, the more intense its use of water with respect to land (Table 5).

Table 4.District identifiers, regression results.

	All 3 crops	Corn	Cotton	Sorghum
Constant	88.88 (3.81)***	85.51 (6.63)***	78.65 (16.55)***	102.9 (-15.31)***
ID004	-24.65 (-3.79)***	-10.32 (-0.78)		-41.95 (-4.65)***
ID006	-47.68 (-9.67)***	-47.52 (-5.20)***		-60.51 (-7.91)***
ID009	-22.46 (-4.21)***	-27.7 (-1.32)	-14.89 (-2.22)**	-34.72 (-4.26)***
ID025	-72.17 (-13.26)***	-66.34 (-6.86)***	-61.89 (-9.21)***	-88.69 (-9.33)***
ID026	-61.6 (-10.93)***	-49.85 (-4.97)***	-54.59 (-7.85)***	-80.79 (-8.21)***
ID031	-28.23 (-3.26)***			-42.25 (-4.11)***
ID050	-58.88 (-9.66)***	-57.96 (-5.22)***		-71.79 (-8.13)***
ID090	-9.83 (-1.83)*	-17.08 (-2.04)**	16.33 (-2.56)**	
ID103	-12.94 (-2.35)**	-8.77 (-1.03)	18.79 (-1.77)*	-34.7 (-3.53)***
F (P-Value)	38.7 (0.00)	12.09 (0.00)	46.42 (0.00)	18.39 (0.00)
R^2 (adj.)	0.61	0.56	0.84	0.58
Obs. (#)	216	72	43	101

† OLS results for Equation (3).

¶With each estimated coefficient appear the t-ratio (in parenthesis) and the significance level for a two-tailed test: * (90%), ** (95%), *** (99%).The same applies for all following tables (Table 5 to Table 7).
Source: Authors'.

Table 5. Geographical coordinates regression results.

	All 3 crops	Corn	Cotton	Sorghum
Cons.	-743.25 (-14.20)***	-716.28 (-7.68)***	-911.43 (-7.86)***	-705.19 (-8.20)***
Lat_j	-3.14 (-3.11)***	-2.37 (-1.33)	-4.18 (-1.58)	-4.17 (-2.65)***
$Long_j$	8.67 (13.86)***	8.18 (8.47)***	10.59 (6.45)***	8.59 (8.11)***
F (P-Val.)	116.38 (0.00)	37.59 (0.00)	41.66 (0.00)	38.73 (0.00)
R^2 (adj.)	0.52	0.51	0.66	0.43
Obs. (#)	216	72	43	101

† OLS results for Equation (3).
Source: Authors'.

The second set of regressions includes as independent variables the districts' environmental conditions: aridity ($Arid_j$) and elevation above sea level ($Elev_j$); organizational characteristics: average size of irrigation plots ($Size_{tj}$) and percentage of irrigated land under private ownership ($Private_{tj}$); and, the seasonal availability of water (w_{stj}), as defined in the previous section. We introduce the explanatory variables in turn and simultaneously. Tables 6a, 6b, 6c, 6d present the OLS regression results. Overall, district-specific environmental conditions explain half or more of observed *NII* variability; plot size associates with nimbler irrigation and private ownership of land, with heavier irrigation; and, water availability shows a numerically small but significant positive effect on the intensity of irrigation water use.

Table 6a: Environment and organization, regression results (all three crops).

Constant	-13.68 (-1.63)	76.20 (12.00)***	-34.14 (-3.27)***	-38.66 (-3.65)***
$Arid_j$	0.027 (5.28)***		0.025 (5.14)***	0.029 (5.59)***
$Elev_j$	0.026 (6.18)***		0.030 (6.18)***	0.028 (5.52)***
$Size_{tj}$		-2.27 (-6.23)***	-1.34 (-4.87)***	-1.36 (-4.98)***
$Private_{tj}$		4.31 (0.35)	55.68 (5.58)***	50.60 (4.97)***
w_{stj}				0.000 (2.12)**
F (P-Value)	120.50 (0.00)	29.83 (0.00)	74.22 (0.00)	61.31 (0.00)
R^2 (adj.)	0.53	0.22	0.59	0.60
Obs. (#)	216	204	204	204

† OLS results for Equation (3).
Source: Authors'.

Table6b: Environment and organization, regression results (corn).

Constant	1.35 (0.10)	64.21 (4.95)***	-24.45 (-1.32)	-23.20 (-1.28)
$Arid_j$	0.017 (2.23)**		0.012 (1.54)	0.015 (1.86)*
$Elev_j$	0.032 (5.11)***		0.039 (4.82)***	0.036 (4.46)***
$Size_{tj}$		-2.67 (-4.16)***	-1.16 (-2.15)**	-1.22 (-2.30)**
$Private_{tj}$		28.92 (1.12)	68.54 (3.24)***	56.97 (2.64)**
W_{stj}				0.000 (1.90)*
F (P-Value)	36.70 (0.00)	11.30 (0.00)	21.21 (0.00)	18.42 (0.00)
R^2 (adj.)	0.50	0.24	0.55	0.57
Obs. (#)	72	66	66	66

† OLS results for Equation (3).
Source: Authors'.

Table 6c: Environment and organization, regression results (cotton).

Constant	-33.96 (-2.01)*	134.67 (9.20)***	-22.99 (-0.69)	-22.65 (-0.67)
$Arid_j$	0.042 (3.52)***		0.031 (2.57)**	0.032 (2.54)**
$Elev_j$	0.012 (0.96)		0.021 (1.34)	0.020 (1.20)
$Size_{tj}$		-3.60 (-4.87)***	-1.35 (-1.83)*	-1.43 (-1.82)*
$Private_{tj}$		-64.19 (-2.53)**	30.31 (0.98)	27.15 (0.83)
W_{stj}				0.000 (0.33)
F (P-Value)	49.73 (0.00)	25.06 (0.00)	26.70 (0.00)	20.85 (0.00)
R^2(adj.)	0.70	0.55	0.72	0.71
Obs. (#)	43	41	41	41

† OLS results for Equation (3).
Source: Authors'.

Table 6d: Environment and organization, regression results (sorghum).

Constant	-23.44 (-1.45)	68.93 (8.34)***	-58.10 (-3.34)***	-70.68 (-3.90)***
$Arid_j$	0.033 (3.46)***		0.040 (4.50)***	0.049 (5.04)***
$Elev_j$	0.021 (3.00)***		0.023 (3.08)***	0.018 (2.28)**
$Size_{tj}$		-1.74 (-3.20)***	-1.82 (-4.53)***	-1.81 (-4.58)***
$Private_{tj}$		4.90 (0.29)	63.33 (4.64)***	56.94 (4.14)***
W_{stj}				0.000 (2.10)**
F (P-Value)	39.58 (0.00)	8.01 (0.00)	30.00 (0.00)	25.77 (0.00)
R^2(adj.)	0.44	0.13	0.55	0.56
Obs. (#)	101	97	97	97

† OLS results for Equation (3).
Source: Authors'.

To assess the robustness of the results presented in Table 6, we re-run all the regressions using three additional functional forms (lin-log, log-lin and log-log) and diagnose the OLS residuals extensively for heteroscedasticity and normality of distribution. We then re-estimate by: OLS using a heteroscedasticity-consistent covariance matrix (HCC); Least Absolute Error (LAE); and, Maximum Likelihood (ML) assuming a gamma distribution for *NII*.

The sign and level of significance of the estimated coefficients prove robust with respect to both the functional form of the model and the regression method employed. For reasons of space, we only present some of those results. Table 7 reports the results for the log-log functional form (of the three mentioned earlier, this one produces the best fit) obtained with the whole dataset (all three crops), as well as some information on the properties of the OLS residuals (a Jarque-Bera test statistics for normality and a White test statistics for heteroscedasticity).

These results reveal useful information about the impact of seasonal availability of water on irrigation intensity. By definition, coefficients reported in Table 7 represent elasticities. Values of between 0.09 and 0.11 reported for the coefficient associated with the seasonal availability of water indicate that a 10% increase in availability leads to an approximately 1% rise in irrigation intensity. We discuss below how this finding sheds light on irrigators' behavior.

Table 7: Environment and organization, re-estimated coefficients (all three crops).

	OLS	OLS-HCC	LAE	ML
Constant	-3.72 (-1.67)*	-3.72 (-1.92)*	-3.50 (-1.30)	-4.68 (-1.87)*
ln $Arid_j$	0.68 (2.04)**	0.68 (2.31)**	0.65 (1.63)	0.81 (2.16)**
ln $Elev_j$	0.32 (4.76)***	0.32 (5.28)***	0.31 (3.88)***	0.29 (4.00)***
ln $Size_{tj}$	-0.12 (-2.23)**	-0.12 (-2.32)**	-0.11 (-1.68)*	-0.13 (-2.21)**
ln $Private_{tj}$	0.30 (2.71)***	0.30 (2.83)***	0.22 (1.63)	0.28 (2.33)**
ln w_{stj}	0.10 (5.74)***	0.10 (5.20)***	0.09 (4.27)***	0.11 (5.91)***
F (P-Value)	87.89 (0.00)			
R^2(adj.)	0.68			
Jarque-Bera (P-Value)	0.49 (0.78)			
White-R^2 (P-Value)	44.53 (0.00)			
Obs. (#)	204	204	204	204

† Results for Equation (3) in log form.
Source: Authors'.

Overall, the results reveal a large amount of variability in irrigation intensity among the MRBG irrigation districts. Local environmental conditions explain a good deal of this variability: net irrigation intensity in the more arid upper basin districts is on average more than twice that in the less arid lower basin districts. This reflects well-known causal relationships: the experimental literature on crop irrigation referred to earlier in this paper makes abundantly clear the basic role of climate in the determination of irrigation requirements.

This experimental line of research has traditionally considered as criterion for optimal irrigation the maximization of land productivity (i.e. yield, the mass of crop obtained per unit of irrigated land). Under that paradigm irrigation intensity is a fixed decision, in the sense that a change in the availability of water from one season to another should only affect the surface of land irrigated, with irrigation intensity left at its yield-maximizing value.

More recently the maximization of water productivity (i.e. the mass of crop obtained per unit of irrigation water) has been proposed as an alternative objective to pursue. Known as “Deficit Irrigation” (DI), the practice consists of a relatively parsimonious use of irrigation water, at some acceptable cost in terms of plant stress and yield. A considerable body of evidence documents the advantages afforded by this strategy in dry, water-short regions (e.g. Geerts and Raes, 2009). DI implies a somewhat flexible irrigation intensity decision, contingent on the level of water scarcity. The positive relationship we find between irrigation intensity and seasonal water availability points to such flexibility in actual irrigation decisions in the MRGB districts. It reflects irrigators’ adaptation behavior in the face of a systematic but variable level of water scarcity.

The statistically significant roles identified for average plot size and the land tenure regime in the determination of irrigation intensity require careful interpretation. These relationships suggest that economic and institutional factors to some extent shape irrigation decisions, however note that they refer to district characteristics and as such do not automatically carry over to individual farmers. For example, while we find that districts with a larger average plot size tend to show lower irrigation intensity, we cannot conclude with certainty that within a given district bigger farmers use water less intensively than smaller farmers. Additionally, plot size and type of land tenure clearly are not direct causes of irrigation intensity. Rather, both factors likely correlate with the fundamental parameters of technology and management practices that determine individual irrigation decisions.

4. CONCLUSIONS

This paper establishes several features of irrigated agriculture of relevance for water policy and management in the MRGB. First and foremost, the basin’s irrigators face systematic water scarcity: in any given year a good portion of available land does not receive irrigation and on the fraction that does, irrigation intensity tends to be lower than what would be the case if more water were available. Moreover, in the future water availability in the basin will likely decrease: climate projections for Southwestern North America (the U.S. South West and Northern Mexico, including the MRGB) suggest increasing aridity for the region (Seager et al., 2007). In this context, transferring water out of agriculture in order to satisfy growing non-agricultural water needs - as practiced today to some extent in the western United States (Doherty & Smith, 2012) - would pose significant challenges. Note furthermore that serious conflict between agricultural and urban water users have already flared up in the recent past in the MRGB (Scott et al., 2007).

Fortunately the heterogeneity in irrigation intensity within the basin opens the opportunity to mitigate the impacts of a reduction (whether climate- or policy-driven) in the volumes of water available for irrigation. Shifting irrigation water use away from the more arid upper basin to the lower basin where water use per unit of irrigated land is about half as great, could potentially free up water for other users without reducing the total surface of irrigated land and thus crop production. Additionally, such a shift in the pattern of water use would naturally increase in-stream flows and thus generate environmental benefits in the river basin.

A detailed proposal for the design of a mechanism to transfer irrigation water from the upper to the lower MRGB lies beyond the scope of this paper, however the existing body of knowledge on water transfers provides several important insights. Over the last decades, accelerated urbanization has spurred water transfers from rural to urban areas in many regions of the world. Garrick et al. (2019a) identify 103 rural to urban water transfer projects involving 69 urban agglomerations, mostly concentrated in North America and Asia and with an estimated 2015 population of 383 million. Mexico ranks among the top five countries with the most experience in the matter, with nine projects implemented to increase water availability for the cities of Guadalajara, Hermosillo, Mexico City and Monterrey. The latter project consists of a water sharing agreement between the Monterrey Metropolitan Area and a lower MRGB irrigation district (ID026 Baja Río San Juan, see Figure 1), extensively described and appraised in Aguilar-Barajas and Garrick (2019).

Overall the experience with rural to urban water transfer projects establishes that they tend to be expensive because of the physical infrastructure investments required. Moreover, the multiplicity and diversity of actors involved (including municipal water authorities, local and national government branches agencies, farmers and other rural actors) lead to time-consuming and complex negotiations, especially around the difficult problem of distributional effects and compensation (Garrick et al., 2019b).

For the case at hand, transferring water from upper to lower basin irrigation districts would require no investments in new infrastructure or additional energy consumption, as water would simply flow through existing reservoirs, channels and waterways. This reduces the issue to having upper basin irrigators draw less water to the benefit of lower basin irrigators.

In Mexico water is national property and a federal agency regulates its use through a system of water rights. Agricultural surface water rights in the MRGB irrigation district are held collectively by Water Users Associations (WUA). A single WUA may aggregate several hundred individual irrigators who share the association’s annual water allocation (which may vary significantly from year to year, depending on weather and water availability) according to their own rules. Moreover WUA members commonly engage in water trades, whereby two individuals exchange water for money for a particular growing season.

Irrigators’ ample experience with water sharing and trading within their own WUA points the way to a mechanism for transferring water at a river basin scale based on consent: a market. The design of a market agglomerating irrigators individually or through their WUA would need considerable thought and consideration. There is little to no prior experience for this in Mexico, where up to now mostly administrative procedures have been employed to regulate and enforce water reallocation projects (Aguilar-Barajas and Garrick, 2019).

In the MRGB and other river basins where similar circumstances prevail, managing water scarcity cannot but prove difficult. Detailed information on water use patterns and practices in agriculture such as offered in this paper should inform the design of the policy solutions needed to meet this challenge in an effective and efficient way.

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