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Economic impacts on irrigated agriculture of water conservation programs in drought

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SUMMARY

The need to adapt irrigation patterns to water shortages in the world's dry regions continues to inspire economically attractive measures to sustain food security and improve farm incomes. Ongoing evidence of climate variability and growing populations amplify the importance of this search. Motivated by recent severe drought in the southwestern United States, this study analyzes vulnerability, impacts, and adaptability by irrigation technology in a sub-basin of North America's Rio Grande. The study accounts for economic incentives affecting choices on irrigation technology, crop mix, and water source in the face of water conservation subsidies under various levels of surface water shortage. Findings show that when surface water supplies are reduced, farmers shift to aquifer pumping even when pumping raises the cost of production or reduces yield. An important on-farm drought adaptation mechanism comes by converting from surface irrigation to water conserving irrigation technologies when faced with lower financial costs for conversion. Public subsidies to convert from flood to drip irrigation offset many of the negative impacts of drought on farm income. These subsidies also raise the value of food production, reduce the amount of water applied to crops, but can increase crop water depletions. Our approach for analyzing drought adaptation impacts and adjustment mechanisms can be applied where water shortages loom, food security is important, and water conservation policies are under debate. Results provide insights for the design of adaptation mechanisms for the world's dry regions for which policymakers need to reduce economic damages from future climate variability and change.

1. Background

Growing populations worldwide, rising international needs for food security, climate change, and increased economic values of water inside and outside irrigated agriculture continue to challenge policy making in both developed and developing communities. These problems challenge the sustainability of economic growth, viability of key ecological assets, and welfare of the poor who bear a large part of the costs of water shortages that could face irrigated agriculture, the world's largest water user. Moreover, by conventional economic valuation standards, irrigated agriculture can produce low economic values of water at the margin compared to uses of water by competing sectors.

The southwestern United States, a very dry place in normal periods, occupies the front lines of challenges faced by the need to adapt to recurrent drought. This drought has been even more severe since 2010. In New Mexico, for example, much of current water planning and policy is based on a historical trend of 6–10 in. precipitation per year. Among other things, it faces international treaty water delivery obligations, federal requirements for endangered species protection, interstate compact delivery obligations, and several water allocation challenges within its borders. When the historical 6–10 in. fail to arrive in a given year, water users suffer cutbacks, with an especially heavy burden shouldered by irrigated agriculture. When the rains fail to arrive for two or more years, rivers, reservoirs, and aquifers face increased pressure of the kind seen in 2010–2013. Examples from 2013 include:

- Irrigation farmers accustomed to 3 acre-feet of surface irrigation water receive 3 in.
- Pecan growers in the Mesilla Valley prune trees to the trunk to make them last.
- Water levels at Elephant Butte Reservoir fall to historic lows.
- Texas sues New Mexico over water shortages in the Mesilla Valley.
- Farmers turn to groundwater pumping to make up for lost river water.

These events have occurred after three very dry years. Water planners are asking what can be done if decades pass before the historical 6- to 10-in. levels of precipitation is restored. What is the best way for water users to adapt to the new normal? Water right ownership brings no wet water. With growing concerns

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about the viability of irrigated agriculture in the drier parts of the US in addition to similar concerns worldwide in the face of recurrent and severe droughts there is a need to find measures to inform policy and management debates on sustainability of agricultural production while responding to rising water scarcity in the face of recurrent drought.

Faced by growing water demands and increased climate variability, recent years have seen much attention on drought scenarios and drought adaptation measures. As a natural hazard, drought can be characterized by several climatological and hydrological indices. A good understanding of the relations between both kinds of indices is needed to establish informed plans to adapt to and mitigate impacts of drought. A recent exhaustive review article in this *Journal* by Mishra and Singh (2010) integrates concepts of drought, drought classification, drought indices, historical droughts viewed by paleo-climatic studies, and the relation between droughts and selected climate indices.

Challenges posed by irrigators who need to adapt to recurrent or severe drought is an ancient problem. But it has seen comparatively little systematic or scholarly work until the late 20th century. Several papers since the early 1990s touched on its various dimensions. An early study from the 1990s found that price-based regulation may not produce water conservation and it also found that conservation policy instruments should be chosen for their capacity to achieve the purposes of water conservation policy (Moore, 1991). Similar work from the US Pacific Northwest found that in the absence of water policy changes in the US, continued irrigation technology adoption could result in an annual water savings of approximately 404,000 acre-feet (Schaible et al., 1991). An early innovative study reviewed the influence of groundwater pumping by irrigators on surface returns to the river system (Suso and Llamas, 1993) extending findings of much earlier studies from the early 1940s. Another work conducted to address issues in developing countries found that where surface water is scarce, drip irrigation can conserve water applications, but its cost of $1000 an acre is prohibitive for most small farmers in developing countries (Polak et al., 1997). Michelsen and his collaborators in 1999 examined the meaning of water conservation found that the term is slippery and hard to define with precision (Michelsen et al., 1999).

Water pricing and marketing measures were found to be an effective resource management measure to promote water conservation (Schuck and Green, 2001) by encouraging reductions in crop water consumption (crop ET). Some early modeling work attempted to identify factors that would promote water conservation in crop irrigation at the basin scale (Cai et al., 2002, 2003).

Later empirical findings suggested that when traditional water conservation technologies are used by farmers, optimization over the entire basin leads to increases in aggregate output when switching from traditional to modern irrigation technology (Chakravorty and Umetsu, 2003). Using several irrigation districts in northern China, analysis found that pricing policies brought little to no water conserved in irrigation under China's current water institutions (Yang et al., 2003). Statistical analyses of water transfers in the Lower Orange River in South Africa showed that only unused water rights were transferred to new uses, while water saved through adoption of conservation practices was retained in the location of origin for security purposes (Nieuwoudt and Armitage, 2004).

More recent modeling work analyzed effects of water costs to find the optimum strategy for farm income maximization, based on its main determining factors such as irrigation system, climate variability, and the like (Ortega et al., 2004). Findings from a study in Colorado and Kansas found that price incentives are likely to have limited impacts on basin-wide water consumption and would make little additional water available for emerging demands (Scheierling et al., 2004; Peterson and Ding, 2005). A similar paper explored the role of economic valuation techniques to inform the design of efficient, equitable and sustainable policies for water resources management in the face of environmental challenges like water pollution (Birol et al., 2006).

Loss of groundwater through increased evapotranspiration (ET) has been reported extensively in the hydrological literature. A 2006 study found that this ET loss could be reduced by a pumping well that reduces the water table within the cone of depression, in spite of the fact that the hydrograph's characteristics affect the proportion of water storage volume returning to the aquifer (Chen and Shu, 2006; Mudd, 2006). By contrast a recent economic analysis found that the price elasticity of agricultural water demand is −0.79, larger in absolute terms than that found in previous studies (Schoengold et al., 2006). Ongoing pressure to develop some of Australia's dryland river basins for irrigation has been reduced with increasing ecological degradation. Work there explored the importance of local and catchment rainfall in contributing to floods (Young et al., 2006).

Pumping in the Ogallala Aquifer of the US state of Kansas has occurred due to expansion of irrigated agriculture. Using a linear programming model, innovative work conducted in that region used a production frontier approach seeking crop irrigation patterns using the least amount of water (Lilienfeld and Asmild, 2007). A study from Tibet integrated a hydrologic and economic analysis that approximated the supply response of conserved water for both irrigated and rain fed crops (Immerzeel et al., 2008).

A 2008 study on the Lower Jordan River Basin found that prices are unlikely to limit groundwater pumping and significant reduction will only be achieved through policies that reduce the number of wells in use, such as regulating or buying existing wells (Venot and Molle, 2008). A study on the Rio Grande Basin of North America found that policies aimed at reducing water applications in irrigated agriculture can actually increase water depletions. Achieving real water savings was found to require designing institutional, technical, and accounting measures that accurately track and economically reward reduced water depletions (Ward and Pulido-Velazquez, 2008; Nixon, 2013). A 2009 study China describes the growth and importance of irrigation in China in terms of the expansion of surface water irrigation led by the state, and the more recent acceleration of groundwater irrigation led by individual farmers (Calow et al., 2009). Results from a 2010 analysis in Iran showed that 88% of added wheat production demands will need to be produced in its water scarce provinces (Faramarzi et al., 2010).

Work from the Murray Darling Basin of Australia made an empirical comparison of two incentive policies to acquire water for environmental flows for the Basin. The first option results in larger return flow reduction, while the second leads to significant irrigated land retirement (Qureshi et al., 2010). A recent study from India found that long-term success of irrigated agriculture for sustainable crop production in that country depends on the careful management of land and water resources (Singh, 2010). Hydrogeological work conducted for the US High Plains Ogallala Aquifer found that the fragmented and piecemeal institutional arrangements for managing water are inadequate to meet the water challenges of the future (Sophocleous, 2010). Work conducted in China found that less government interference in the implementation of water conserving policy instruments and institutions is likely to enhance both ecological and economic benefits (Qu et al., 2011). Another work from China examined the problem of groundwater overdraft as it threatens the future of irrigated agriculture in the North China Plain. Widespread implementation of measures that reduce depth of irrigation water applied (regulated deficit irrigation) could produce a significant water savings with an economic benefit if managed carefully (Zhang et al., 2011). Work from Iran found that an irrigation conservation subsidy policy is likely to incur a high cost to the taxpayer, but it could be economically attractive for both irrigators and environmental stakeholders (Nikouei et al., 2012).

The works described above present some of the many recent contributions to the literature on the economics of water conservation in irrigated agriculture conducted since the early 1990s. Despite the importance of these contributions individually, little published work to date has integrated economic, hydrologic, financial, and institutional principles to explain choices made on crop water use, crop mix, land in production, irrigation technology, and the resulting economic value of water in crop irrigation, while also making a distinction between water applied versus water depleted by crops.

Because of these gaps in the literature dealing with adaptation by irrigation to water shortages of various levels of severity, this paper's mission is driven by the need to fill the gaps described above. This paper attempts to fill those gaps by integrating hydrology, agronomy, institutions, economics, and policy. This integration is conducted to inform policy and management debates on measures to sustain agricultural production while responding to rising water scarcity in the face of recurrent drought and growing water demands for all water uses. It fills these gaps by examining vulnerability to drought and economic consequences to irrigated agriculture and by identifying mechanisms to promote its adaptation. This aim is achieved by taking the following steps:

- Assembling historical data on water applied, water consumed, crop yield, land in production, mix of crops in production, and crop profitability by irrigation technology and source of water.
- Conceptually integrating the microeconomic theory governing the demand for water in irrigated agriculture with observed data on crop water use data into a framework suitable for empirical analysis.
- Applying the framework to forecast water applications, water depletions, land use, crop production, farm income, and the economic value of water for a range of drought scenarios and water conservation subsidies.

Our analysis is applied to irrigation in the Upper Rio Grande Basin, shown in Fig. 1. That Basin extends from the headwaters in southern Colorado's Rocky Mountains to about 100 miles downstream of El Paso, Texas, USA. The analysis focuses on a sub-basin of that larger basin, located in southern New Mexico. Its scope includes lands irrigated in New Mexico from the outflow of Elephant Butte Reservoir to a point about 120 miles south of that point on the New Mexico–Texas geographic border. Heavy water use by irrigated agriculture has occurred in this region since the 1600s in what is now the Elephant Butte Irrigation District (EBID). In that region growing values of water for cities and the environment, illustrate the hydrologic, economic, and political importance of discovering ways to adapt to surface water drought. Severe drought defined by ongoing major shortages in surface water has occurred in this region for 2011–2013. For the year 2013, growers received about 2 in. of surface water per acre in the project area that since 1916 has received 36–40 in. in a full supply year. So there is considerable and ongoing interest in economically viable measures that could promote economically attractive water conservation measures in irrigated agriculture.

2. Approach

2.1. Conceptual framework

The economic analysis described in this paper is based on an empirical farm income optimization model to inform ongoing policy debates dealing with the effectiveness of water conservation subsidies for irrigated agriculture. Several pages of detail are included in the attached mathematical Appendix. The analysis described here conducts a "with versus without policy" comparison for a water conservation subsidy that would reduce producers' capital costs of converting from surface to drip irrigation. Under the proposed program, growers would substitute increased irrigation infrastructure (at a cost) for reduced water applications per unit land irrigated. The importance of access to affordable substitutions of water conserving irrigation infrastructure for reduced surface water supplies takes on more importance in the face of growing shortages in surface water supplies. The economic principle behind water conservation is to substitute increased irrigation infrastructure and its associated financial cost for reduced water application rates for any given crop. The mathematical relationships that integrate hydrology, agronomy, institutions, water rights administration, economics, and impacts of a water conservation subsidy on choices made by irrigators are presented in the mathematical Appendix.

2.2. Data

Table 1 shows data used for the analysis. Average income per acre by crop and irrigation technology equals price multiplied by yield minus average costs. It equals the average (not marginal) economic value of water per acre foot. Data on costs and returns, water applications, water depletions, land in production, and total income earned are shown in the table by irrigation technology for cotton, alfalfa, lettuce, onions, red chile, green chile, and pecans.

The table shows that average income per acre shows considerable variability among crops and irrigation technology for land in production under base conditions. In addition to these facts shown in the table, microeconomic theory provides the significant added insight that incomes under base conditions are not maximized unless the value of the marginal product of water equals the price of water for each crop and irrigation technology. The price of surface water for our study area is an administered price, set to approximately \$52 per acre foot applied. That identical price is administered under all water supply conditions, even when surface water supplies approach zero. So we faced the challenge of calculating a set of parameters to make the observed behavior consistent with an income maximization behavior for which the value of the marginal product of water is inferred to be \$52 per acre foot applied.

Maximizing total regional irrigation farm profitability for any crop requires expanding water and associated land in production for each crop as long as additional revenues exceed additional costs. There is a fixed water use requirement per unit land for any given crop, shown as both water application rates and water depletion rates in the columns showing water applied and water consumed. The current paper does not address regulated deficit irrigation.

An earlier article describes the use of positive mathematical programming (PMP) in which parameters are estimated for a linear crop yield production relation in which yields decline linearly with expanded acreage brought into production (Dagnino and Ward, 2012). For each crop and irrigation technology, the first lands brought into production have the highest yields, while the most marginal land currently in production have lower yields. Lands not currently in production (unseen) would produce even lower yields, explaining why these lands do not enter production under baseline observed conditions. Yield for each crop and irrigation technology decline with expanded acreage. Maximum yields for the first unit of land entering production are shown in the table as well as the marginal impact of additional acreage on yields, always a negative term. Under full supply (base) conditions, there is little to no groundwater pumped, so maximum and marginal yields are not shown where groundwater irrigation could occur.

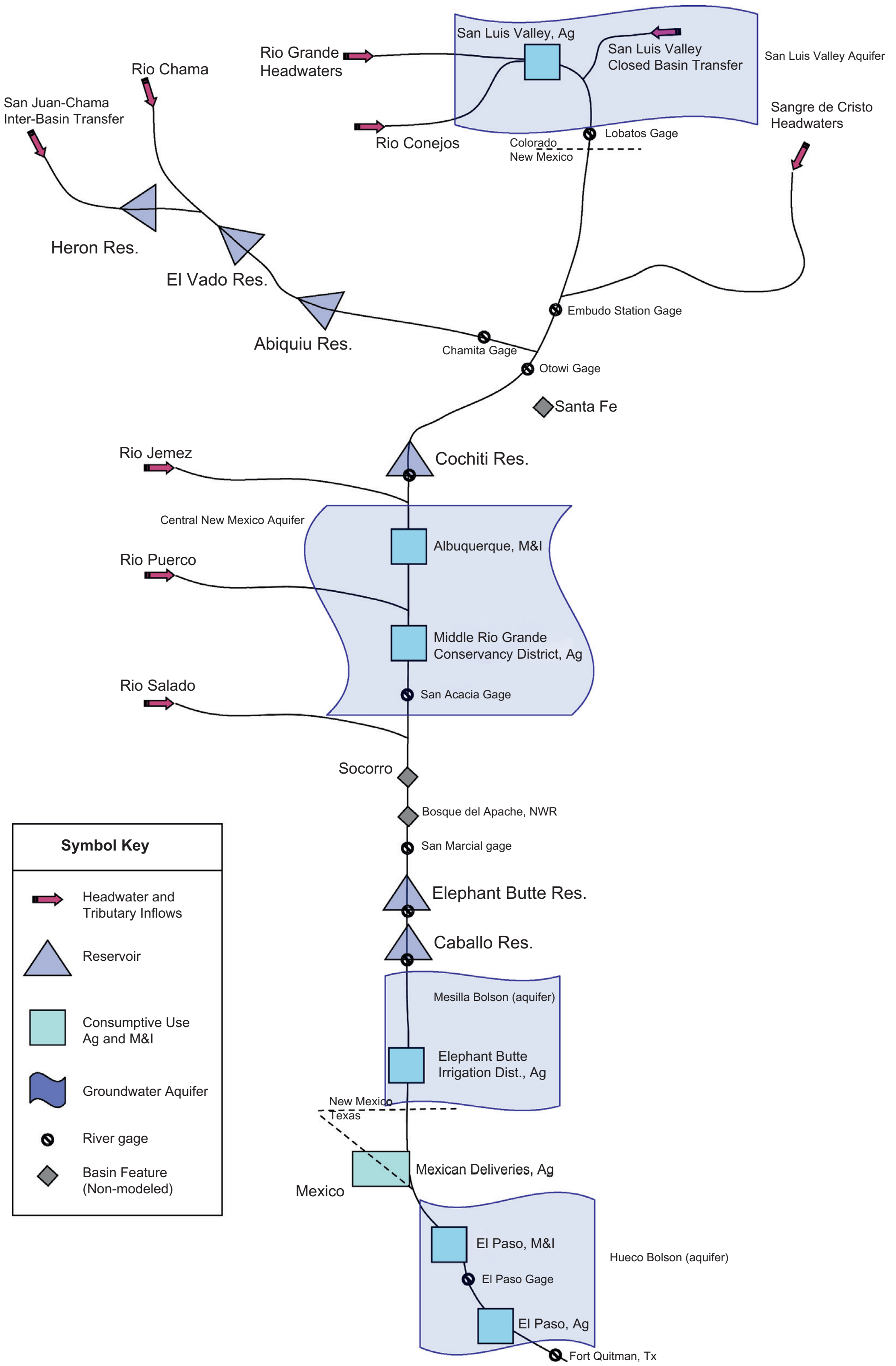

Fig. 1. Rio Grande Basin schematic.

An important application of the PMP approach to actual policy decisions lies in applying the calculated yield parameters by crop and irrigation technology to future water supply scenarios or future subsidies from converting from surface to drip irrigation. Alternative future water supply possibilities are shown, in which water supplies are limited to 80%, 60%, 40%, 20%, and 0% of full surface supply levels. In addition, subsidies for converting from surface to drip irrigation are set at the baseline level (0% conversion subsidy) and also one alternative level (100% conversion subsidy). Other subsidy levels can be analyzed.

Table 1
Base observed data on irrigation profitability by crop, technology, and source of water, Lower Rio Grande Project, New Mexico, USA, 2013.

Crop	Technology	Source	Price ($US/ton)	Yield (tons/ac)	Cost ($US/ac)	Net income ($US/ac)	Water applied (ac-ft/ac)	Water consumed (ET) (ac-ft/ac)	Land in production (ac)	Maximum yield (B_0) (tons/acre)	Marginal yield (B_1) Δ (tons/ac)/Δac	Total income ($/yr)
1-alfalfa	1-flood	1-sw	160	8.00	819	461	5.00	3.26	14,821	10.88	−0.000195	6,836,214
		2-gw	160	7.20	943	209	5.00	3.26	0	[a]	[a]	0
	2-drip	1-sw	160	9.00	1299	141	4.08	3.67	780	9.88	−0.001129	109,924
		2-gw	160	8.10	1439	−143	4.08	3.67	0	[a]	[a]	0
2-cotton	1-flood	1-sw	2700	0.42	847	287	3.00	2.29	12,930	0.53	−0.000008	3,711,043
		2-gw	2700	0.42	934	200	3.00	2.29	0	[a]	[a]	0
	2-drip	1-sw	2700	0.46	1195	47	2.79	2.51	1279	0.48	−0.000014	60,633
		2-gw	2700	0.46	1290	−48	2.79	2.51	0	[a]	[a]	0
3-lettuce	1-flood	1-sw	305	11.88	3374	250	2.50	1.50	2640	12.70	−0.000310	659,168
		2-gw	305	8.91	3431	−713	2.50	1.50	0	[a]	[a]	0
	2-drip	1-sw	305	13.83	4081	137	1.94	1.75	360	14.28	−0.001246	49,253
		2-gw	305	10.37	4148	−984	1.94	1.75	0	[a]	[a]	0
4-onions	1-flood	1-sw	275	16.88	4317	329	4.00	2.30	2670	18.07	−0.000447	877,904
		2-gw	275	11.82	4404	−1152	4.00	2.30	0	[a]	[a]	0
	2-drip	1-sw	275	20.08	5324	202	3.04	2.74	330	20.81	−0.002223	66,623
		2-gw	275	14.06	5428	−1560	3.04	2.74	0	[a]	[a]	0
5-green_chile	1-flood	1-sw	245	11.00	2492	203	3.00	2.00	1335	11.83	−0.000620	270,538
		2-gw	245	8.25	2569	−547	3.00	2.00	0	[a]	[a]	0
	2-drip	1-sw	245	13.25	3168	78	2.68	2.41	165	13.57	−0.001924	12,831
		2-gw	245	9.94	3260	−826	2.68	2.41	0	[a]	[a]	0
6-red_chile	1-flood	1-sw	1440	1.75	2154	366	3.00	2.00	1335	2.00	−0.000190	488,824
		2-gw	1440	1.31	2230	−340	3.00	2.00	0	[a]	[a]	0
	2-drip	1-sw	1440	1.95	2700	108	2.48	2.23	165	2.03	−0.000455	17,854
		2-gw	1440	1.46	2785	−679	2.48	2.23	0	[a]	[a]	0
7-pecan	1-flood	1-sw	4560	0.58	1864	781	5.00	2.99	20,020	0.75	−0.000009	15,627,394
		2-gw	4560	0.52	1978	402	5.00	2.99	0	[a]	[a]	0
	2-drip	1-sw	4560	0.72	3016	267	4.12	3.71	1980	0.78	−0.000030	528,191
		2-gw	4560	0.65	3158	−203	4.12	3.71	0	[a]	[a]	0
Total									60,810			29,316,391

[a] Unobserved.

2.3. Application

Our economic analysis of irrigation water use rests on the foundation of farm-level economics. The observed data are based on the use of enterprise budgets. These budgets provide detailed financial information regarding surface-irrigated crop production, including crop acreage, equipment, crop production processes, and overall summaries of crop costs and returns. The farm budgets are published by the New Mexico State University Extension Service, and contain detailed financial data for agricultural production. About 90% of the land in production in this region is irrigated by surface irrigation, and is virtually all irrigated by surface river water (not from the aquifer) when full allocations of surface water runoff are available. As supplies of surface water decline with a drought of growing intensity, growers typically substitute groundwater pumping for surface water applications.

As a long term drought adaptation measure, conversion from surface to drip irrigation typically is expensive, and requires specialized management practices. The drip irrigation budgets we developed reflect this difference by incorporating the additional equipment required, difference in purchased inputs, differences in labor requirements, and most importantly, savings in applied water. The economic decision to convert from surface to drip irrigation depends on observed as well as anticipated future input and output prices and costs. A detailed mathematical documentation is appended.

Growers require an economic advantage to convert from surface to drip irrigation or other measures that substitute irrigation infrastructure for water applied. Growers typically convert to drip irrigation not to conserve water but to secure higher economic return from irrigation through increased yields, reduced costs of water, and reduced variable production costs. This is an especially important motivation facing growers in conditions where surface water is abundant and/or priced at or near zero. The enterprise budget approach permits a systematic incorporation of the economics of private on-farm decision making that analyzes impacts of drought or public water conservation subsidies.

Drip irrigation applies small amounts of water to the crop's root zone at a slow but steady rate. In the EBID service area, where practiced, drip tapes distribute the water and are typically buried to a depth of 8–10 in. (1 in. = 2.54 cm) below the surface in order to reach the crop root zones. The difference between surface and drip irrigation technology carries important implications for choices by growers that can influence water conservation. The close interaction between the root zone and water source allows the irrigator to divert less water from the stream and apply less water to a given field than is normally applied under surface irrigation.

The conversion from a surface to drip irrigation system typically increases crop evapotranspiration (ET) because of attendant higher crop yields that consume more water. A crop's water requirement for full yields does not change with the use of drip irrigation. However, higher yields can occur when the drip irrigator avoids deficit irrigation which can be harder to avoid under surface irrigation. Drip irrigation attempts to supply water directly to the root zone, increasing the percentage of applied water that reaches the plant, typically increasing yields.

Installation costs for drip irrigation systems are amortized using information on the total cost of the system, system life, and the interest rate. For this analysis, the cost used is $2500 per acre for

Table 2
Water applications by surface water available, drip conversion subsidy, irrigation technology, and source of water, Lower Rio Grande Basin, USA, 2013 (a-f/yr).

Surface supply (percentage of full supply)	Drip subsidy (percentage of conversion costs)	Irrigation technology (ac-ft/yr)				Total surface water applications (ac-ft/yr)	Total groundwater applications (ac-ft/yr)	Total water applications (ac-ft/yr)	Weighted average water applications (ac-ft/ac)
		1-flood Water source (ac-ft/yr)		2-drip					
		1-sw	2-gw	1-sw	2-gw				
1–100	1–0	238,285	0	17,460	0	255,745	0	255,745	4.21
	2–100	215,587	0	34,206	0	249,793	0	249,793	4.12
2–80	1–0	199,437	20,027	11,145	0	210,582	20,027	230,609	4.29
	2–100	181,143	15,647	24,158	3715	205,300	19,362	224,662	4.19
3–60	1–0	153,514	52,279	8324	0	161,838	52,279	214,117	4.30
	2–100	145,017	37,840	14,083	11,125	159,099	48,965	208,065	4.19
4–40	1–0	101,852	102,527	7238	0	109,090	102,527	211,617	4.34
	2–100	107,962	73,142	3225	21,117	111,187	94,259	205,446	4.23
5–20	1–0	56,243	148,435	0	6716	56,243	155,150	211,393	4.35
	2–100	56,312	126,956	0	22,401	56,312	149,357	205,669	4.26
6–00	1–0	0	190,992	0	6284	0	197,275	197,275	4.47
	2–100	0	170,722	0	21,347	0	192,069	192,069	4.36

a system that has an expected life of 10 years with an interest rate of 5.0%. Amortizing produces an annual payment amount that accounts for the life of the loan, total capital cost, and interest.

The resulting annual equivalent cost was $324 per acre for the case of 0% capital conversion subsidy for the region's producers. This sizeable investment of $2500 per acre for a 10 year life is the expense that a public water conservation subsidy aims to reduce in order to make reduced water applications in irrigated agriculture more economically attractive. The standard amortization formula was used to account for varying reductions in the capital cost associated with increasing the public subsidy from 0% to 100% of the capital costs of conversion.

Drip irrigation systems in Lower Rio Grande Project Area typically require field flushing of accumulated salts once per growing season, often done at the end of the season. This is a significant best management practice (BMP), needed to reduce soil salinity levels, which also incurs the additional cost of finding the water supply to perform the flush. Surface irrigation provides the flush during the normal course of irrigation; drip irrigation systems do not experience flushing because irrigation water applications are emitted slowly and intermittently to the root zone of the crop.

3. Results

3.1. Water applied

Table 2 shows water applications by surface water available, drip conversion subsidy, irrigation technology, and source of water for the project area. It shows that reduced quantities of surface water are applied to crops as the surface supply drought intensifies. It also shows that a widespread substitution of water pumped for surface water applied as surface supplies are reduced.

The table shows that a flood-to-drip conversion subsidy produces a considerable shift in water application favoring greater quantities of water applied by drip technology compared to the far more conventional surface application seen in the region. As expected total surface water applications are reduced as surface supplies become scarce, but they also fall off with a higher drip irrigation conversion subsidy. Most important, total applications summed over the project area acreage fall off in the face of reduced surface supplies and also in the face of a surface-to-drip conversion subsidy. Average applications over the entire project area, measured in terms of average irrigation depth always lie between 4.0 and 4.5 feet depth. This result shows a modest pattern of reduced acreage with greater quantities of water applied per remaining acre as surface water becomes scarce.

3.2. Water depleted

Table 3 shows water depletions by surface water supply, drip conversion subsidy, irrigation technology, and source of water. This table shows similar patterns as presented in Table 2. The main difference is that neither surface water depletions nor groundwater depletions are allowed to increase in the face of a surface-to-drip conversion subsidy. These depletions are not allowed to increase because of the way water rights are administered in New Mexico. Rights are administered to protect water right holders from increased depletions in the face of drip irrigation subsidies or in the face of other polices.

Administering water rights in this way occurs in New Mexico as a protective measure to keep the river system whole. It protects water rights holders that depend on supplies that could otherwise be reduced when greater irrigation efficiency is achieved by irrigation infrastructure subsidies.[1] Water administrators are constantly reminded that one water user's "sloppy" water management (low irrigation efficiency) is another user's water supply.

Attempts to administer programs that avoid increased water depletions with irrigation infrastructure subsidies are often based on raising irrigation efficiency, the percentage of river system water that reaches the plants' root zones. Nevertheless, attempts to reduce water depletions can present considerable difficulties with enforcement. This occurs because water applications can be measured with good metering systems, but water depletions are more difficult to measure and may require considerable investments in technology and/or enforcement. Large intellectual, financial, and time investments are required for measurement systems such as lysimeters, water balance and eddy covariance calculations, energy balance, mass transfer, estimation of crop coefficients, flux towers, and remotely sensed imagery. One lower cost method of water administration could protect against increased depletions in the face of infrastructure subsidies by simply

[1] For example, the US EQIP (Environmental Quality Incentives Program) enacted in 1996, established several kinds of irrigation infrastructure eligible for taxpayer support. A few examples include sprinklers, irrigation pipelines, drip irrigation equipment, land leveling, pumping plant improvement, irrigation ditch lining, on-farm irrigation reservoirs, and tailwater recovery.

Table 3
Water depletion by surface water available, drip conversion subsidy, irrigation technology, and source of water, Lower Rio Grande Basin, New Mexico, USA, 2013 (a-f/yr).

Surface water available (pct of full surface supply)	Drip conversion subsidy (pct of conversion cost)	Irrigation technology (ac-ft/yr)				Total surface water depletions[a] (ac-ft/yr)	Total groundwater depletions[a] (ac-ft/yr)	Total depletions (ac-ft/yr)	Groundwater depletions as a proportion of total depletions (ac-ft/yr)	Drip irrigation depletions as a proportion of total depletions (ac-ft/yr)	Overall water depletions (weighted average) (ac-ft/ac)	Overall irrigation efficiency (weighted average) (0–100%)
		1-flood Water source (ac-ft/yr)		2-drip								
		1-sw	2-gw	1-sw	2-gw							
1–100	1–0	153,227	0	15,714	0	168,941	0	168,941	0.00	0.09	2.78	66
	2–100	138,156	0	30,785	0	168,941	0	168,941	0.00	0.18	2.79	68
2–80	1–0	125,123	15,287	10,030	0	135,153	15,287	150,440	0.10	0.07	2.80	65
	2–100	113,411	11,944	21,742	3343	135,153	15,287	150,440	0.10	0.17	2.81	67
3–60	1–0	93,873	37,748	7492	0	101,365	37,748	139,113	0.27	0.05	2.79	65
	2–100	88,691	27,735	12,674	10,013	101,365	37,748	139,113	0.27	0.16	2.80	67
4–40	1–0	61,063	69,759	6514	0	67,577	69,759	137,335	0.51	0.05	2.82	65
	2–100	64,674	50,753	2903	19,005	67,577	69,759	137,335	0.51	0.16	2.83	67
5–20	1–0	33,788	97,211	0	6044	33,788	103,255	137,044	0.75	0.04	2.82	65
	2–100	33,788	83,095	0	20,161	33,788	103,255	137,044	0.75	0.15	2.84	67
6–00	1–0	0	122,660	0	5655	0	128,316	128,316	1.00	0.04	2.91	65
	2–100	0	109,103	0	19,212	0	128,316	128,316	1.00	0.15	2.91	67

[a] Water use administered to protect water right holders from increased depletions in the face of drip irrigation subsidies that raise crop water ET.

guarding against more land coming into production in the face of conversion from flood to drip irrigation.

3.3. Yields

Table 4 shows crop yield by surface water available, water source, irrigation technology, drip conversion subsidy, and crop in the project area. Observed yields are presented for the base case. This base case is defined by full surface water supply, no drip conversion subsidy, and no groundwater pumping irrigation (shaded cells). The remaining cells show predicted (not observed) crop yields under several combinations of counterfactual (non-base) conditions.

The table shows results produced by the yield relations shown in Appendix Eqs. (A8) and (A9). Other things equal, yields irrigated from groundwater pumping are lower than yields produced by irrigation from surface water because of elevated salinity levels associated with pumping. Yield losses produced by elevated salinity from groundwater applied to irrigation in 2013 are highest for onions and are lowest for cotton. Cotton is fairly salt tolerant in this region.

Generally, the table shows that as surface supplies are reduced in a more severe surface water shortage (lower rows in the table) smaller amounts of lands are surface irrigated, raising yields on those remaining (more productive) lands for which the reduced quantities of surface water are applied. Yields are typically higher under drip irrigation than flood irrigation and also tend to be lower under drip irrigation as the surface-to-drip conversion subsidy increases. This unexpected result occurs because an increased subsidy brings more land into production under drip irrigation as growers take advantage of the subsidy. It illustrates the principle of Ricardian rent, in which less productive more marginal lands are brought into production with a growing conversion subsidy, permitting lower yields on those more marginal lands to pass the threshold of profitability instead of being unprofitable.

3.4. Income

Table 5 shows farm income achieved by percentage of full surface water allocation, drip conversion subsidy, irrigation technology, and water source, for the project area. Results are entirely consistent with findings presented above. As expected, greater shortages of surface water exact a growing toll on farm income earned from surface irrigation. However, the project area has a very abundant aquifer available as a backstop source for which pumping costs as of 2013 average about $90 per acre foot.

Access by growers with installed pumping capacity to use the aquifer's water softens the blow considerably of the surface water shortage. In fact as surface supplies fall to zero, results show that growers can maintain nearly half the income they would earn with full water supplies ($13.8 million without drip irrigation subsidies and $15.1 million with those subsidies). As the surface drought falls from 100% to 0% of full supplies, the percentage of income contributed by groundwater pumping rises from 0% to 100%.

Interestingly, there are two conditions in which income from drip irrigation from groundwater sources is negative. This negative income comes from the requirement that all pecan acreage stays in production by whatever means are possible to avoid an irreversible loss of orchards. A small income loss in the current year is preferred to losing an entire orchard. When surface flows fall below 40% of full supplies, drip irrigation from surface sources cannot be relied onto save the trees. Income losses are magnified by the size of the surface water drought, but are mitigated by subsidies that reduce the cost of converting from flood to drip irrigation.

3.5. Marginal economic value of water depleted

Fig. 2 shows the economic value of an additional acre foot of water if it could be made available from measures that would increase its supply. This shadow price measures the additional annual farm income from making one more acre foot available for crop irrigation. Equivalently, it is the farm income lost from reducing the entire project area's supply of water by one acre foot.

The shadow price shows the opportunity cost, measured as farm income that would be lost by not adding capacity that could have produced an additional depletable acre foot of supply. The table shows shadow prices by water supply level, drip irrigation subsidy, and water source. These shadow prices provide important information supporting decisions by farmers, farm managers, and policymakers who wish to make investments in finding and/or developing alternative sources of water. Examples of such alternative sources include additional groundwater pumping, water

Table 4
Crop yield by surface water available, water source, irrigation technology, water conservation subsidy, and crop, Rio Grande Project Area, New Mexico, USA, 2013 (tons/acre).

			Crop													
			1-alfalfa Conversion subsidy (percent of conversion cost)		2-cotton		3-lettuce		4-onions		5-green_chile		6-red_chile		7-pecan	
			1–0 (tons/acre)	2–100	1–0	2–100	1–0	2–100	1–0	2–100	1–0	2–100	1–0	2–100	1–0	2–100
1–100	1-sw	1-flood	8.00	8.37	0.42	0.44	11.88	11.97	16.88	17.03	11.00	11.15	1.75	1.78	0.58	0.59
		2-drip	9.00	8.41	0.46	0.42	13.83	13.40	20.08	19.67	13.25	12.77	1.95	1.87	0.72	0.69
	2-gw	1-flood	7.20	7.53	0.42	0.44	8.91	8.98	11.82	11.92	8.25	8.36	1.31	1.33	0.52	0.53
		2-drip	8.10	7.57	0.46	0.42	10.37	10.05	14.06	13.77	9.94	9.58	1.46	1.40	0.65	0.63
2–80	1-sw	1-flood	8.39	8.76	0.44	0.45	11.97	12.06	17.04	17.19	11.16	11.30	1.78	1.80	0.58	0.59
		2-drip	9.44	8.84	0.48	0.43	13.94	13.51	20.27	19.86	13.44	12.96	1.98	1.90	0.72	0.70
	2-gw	1-flood	7.55	7.88	0.44	0.45	8.98	9.05	11.93	12.03	8.37	8.48	1.33	1.35	0.52	0.53
		2-drip	8.49	7.96	0.48	0.43	10.45	10.13	14.19	13.90	10.08	9.72	1.48	1.42	0.65	0.63
3–60	1-sw	1-flood	8.79	9.18	0.44	0.45	12.08	12.17	17.22	17.37	11.33	11.48	1.81	1.83	0.58	0.59
		2-drip	9.88	9.25	0.48	0.43	14.06	13.64	20.48	20.08	13.57	13.17	2.01	1.93	0.72	0.70
	2-gw	1-flood	7.91	8.26	0.44	0.45	9.06	9.13	12.05	12.16	8.50	8.61	1.35	1.37	0.52	0.53
		2-drip	8.89	8.33	0.48	0.43	10.55	10.23	14.34	14.05	10.18	9.88	1.51	1.45	0.65	0.63
4–40	1-sw	1-flood	8.72	9.11	0.44	0.45	12.19	12.27	17.41	17.54	11.51	11.65	1.84	1.86	0.58	0.59
		2-drip	9.88	9.25	0.48	0.43	14.19	13.75	20.71	20.28	13.57	13.37	2.03	1.96	0.73	0.70
	2-gw	1-flood	7.84	8.20	0.44	0.45	9.14	9.20	12.19	12.28	8.64	8.74	1.38	1.40	0.52	0.53
		2-drip	8.89	8.33	0.48	0.43	10.64	10.32	14.50	14.20	10.18	10.03	1.52	1.47	0.66	0.63
5–20	1-sw	1-flood	8.72	9.06	0.44	0.45	12.19	12.27	17.41	17.54	11.51	11.65	1.84	1.86	0.58	0.59
		2-drip	9.88	9.20	0.48	0.43	14.28	14.28	20.81	20.81	13.57	13.57	2.03	2.03	0.73	0.70
	2-gw	1-flood	7.84	8.16	0.44	0.45	9.14	9.20	12.18	12.28	8.64	8.73	1.38	1.39	0.52	0.53
		2-drip	8.89	8.28	0.48	0.43	10.71	10.71	14.57	14.57	10.18	10.18	1.52	1.52	0.66	0.63
6–00	1-sw	1-flood	8.72	9.11	0.44	0.45	12.70	12.70	18.07	18.07	11.83	11.83	2.00	2.00	0.58	0.58
		2-drip	9.88	9.25	0.48	0.43	14.28	14.28	20.81	20.81	13.57	13.57	2.03	2.03	0.73	0.71
	2-gw	1-flood	7.84	8.20	0.44	0.45	9.52	9.52	12.65	12.65	8.87	8.87	1.50	1.50	0.52	0.53
		2-drip	8.89	8.33	0.48	0.43	10.71	10.71	14.57	14.57	10.18	10.18	1.52	1.52	0.66	0.63

Table 5
Regional farm income by surface water allocation, drip conversion subsidy, irrigation technology, and water source, Lower Rio Grande Project Area, New Mexico, USA, 2013 ($US per year).

Surface water supply (percent of full allocation)	Drip conversion subsidy (percent of conversion cost)	Irrigation technology ($/year)				Total income from surface water ($/year)	Total income from groundwater ($/year)	Total income from all water sources ($/year)	Income lost, by surface supply and drip conversion subsidy (base is no subsidy and full surface supply) ($/year)
		1-flood Water source ($/year)		2-drip					
		1-sw	2-gw	1-sw	2-gw				
1–100	1–0	28,471,085	0	845,307	0	29,316,391	0	29,316,391	0
	2–100	28,214,135	0	3,626,086	0	31,840,221	0	31,840,221	−2,523,830
2–80	1–0	26,015,123	1,624,813	742,263	0	26,757,386	1,624,813	28,382,199	934,192
	2–100	25,553,065	1,487,228	2,914,077	276,241	28,467,142	1,763,469	30,230,612	−914,221
3–60	1–0	21,790,213	3,920,283	612,170	0	22,402,383	3,920,283	26,322,666	2,993,725
	2–100	21,877,669	3,380,274	1,872,690	773,195	23,750,359	4,153,469	27,903,828	1,412,563
4–40	1–0	15,351,059	7,237,515	551,857	0	15,902,916	7,237,515	23,140,431	6,175,960
	2–100	17,226,756	5,961,233	557,970	861,610	17,784,726	6,822,843	24,607,569	4,708,822
5–20	1–0	8,315,354	10,811,513	0	−261,047	8,315,354	10,550,466	18,865,820	10,450,572
	2–100	8,853,162	10,416,527	0	908,213	8,853,162	11,324,740	20,177,902	9,138,489
6–00	1–0	0	14,054,665	0	−224,877	0	13,829,788	13,829,788	15,486,603
	2–100	0	14,154,096	0	922,744	0	15,076,840	15,076,840	14,239,551

importation, desalination, water conservation, mitigating climate variability, (proven) weather modification, rainwater harvesting (if it avoids displacing existing surface or groundwater supplies). Institutional measures for finding additional supply include things like renegotiating interstate water compacts, completing adjudications of the Basin, and introducing water banks.

The figure shows that the shadow price is $38 for an extra acre foot of depletable water when total surface water supply depletions are limited to a normal full supply. That amount is 168,941 per year, covering about 70% of the district's cropped acreage. Water managers may wish to know whether it pays to add capacity for finding additional water supply. Examples of ways to make additional water available include infrastructure developed for recycling, reuse, urban water conservation, weather modification, rainwater harvesting, development of brackish groundwater, and water importation.

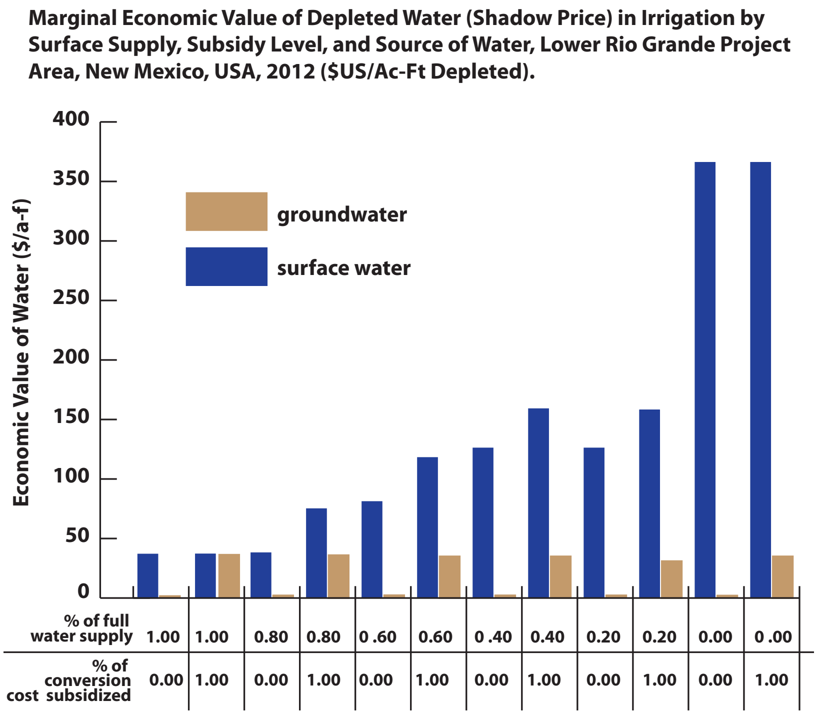

Fig. 2. Marginal values of water for irrigation, Rio Grande Project Area, USA, 2013.

Several shadow prices are shown in Fig. 2, one for each combination of six surface water supply conditions, two drip irrigation conversion subsidies, for each of two sources of water. Several patterns emerge:

1. As surface water supplies decrease from 100% of a full allocation of depletable supplies (168,941 ac-ft/yr) to 0% of full, the shadow price increases from a low level of zero at full supply with no drip irrigation subsidies to a high level of more than $300 per acre foot.
2. Interestingly, the shadow price of groundwater pumping is not always zero. This occurs because irrigators have an effective upper bound on additional groundwater pumped in the face of a growing subsidy for converting from flood to drip irrigation, in which crop ET is likely to increase with associated reductions in groundwater recharge.
3. Even in the face of growing surface water shortages, total water depleted by crops is nearly maintained at base levels (168,941 ac-ft). While total depletions are nearly maintained, a growing percentage comes from groundwater pumping as surface supplies fall and/or as the drip irrigation subsidy increases.
4. Even in conditions of extreme shortage when virtually nearly no surface supplies remain in the river (approximately 2013 conditions), the marginal value of additional surface water depletions rises to a high of more than $300 per acre foot as long as there is affordable access to groundwater, currently about $90 per acre foot pumped. Shadow prices of depletable surface water would be considerably higher without access to groundwater, as was discovered in much of mid America in the Dust Bowl of the 1930s, for which groundwater pumping had not yet been developed to substitute for surface water that occurred with shortages of rainfall.

The tabled shadow prices inform managers, extension professionals, farmers, and water administrators about the scarcity value of depletable water for crop irrigation. That shadow price is shown to vary considerably according to the water conservation subsidy level and water supply scenario. A higher conservation subsidy and a lower depletable supply both raise the shadow price of surface water. The growing economic value of depletable water with a rising drip irrigation subsidy occurs because water administration in New Mexico aims to protect water rights by guarding against increasing river system depletions in the face of alternative drought adaptation methods.

For any given water supply scenario, the region's water administrator (State Engineer) is required by law to take steps to guard against increased net depletions on the river system. Water rights in New Mexico are based on the right to consume water, not the right to apply it. Despite the legal requirement to protect water rights holders from increased water depletions that would otherwise occur in the face of irrigation water infrastructure subsidies, farmers recognize well that increased surface-to-drip conversion subsidies raise the profitability of cultivating crops with drip irrigation.

These economic and hydrologic challenges raise the importance of protecting against the increased water depletions that a growing drip irrigation subsidy could otherwise promote. Protecting the stream–aquifer system and the basin's water rights holders against increased depletions can be achieved by on-farm actions that reduce land in production, such as simple regulations or public purchases of water or water rights for urban or environmental purposes. Without water administrators taking active steps to reduce irrigated land in production in the face of greater public subsidies of drip irrigation, total depletions could rise as growers convert to drip irrigation from surface irrigation thanks to higher greater crop yields and associated higher ET to support those higher yields.

Irrigators may interpret their water right as the right to apply up to a base amount of water on their land rather than the right to deplete no more than a base depletion level. Depletion is harder to measure than application. Where this view of a potentially unused water right occurs, farmers can be expected to adjust their crop mix and bring in additional irrigated land into production to fully use their base right to apply water when responding to a subsidy for converting from surface to drip irrigation. Because of the reduced water applications associated with farmers who convert to infrastructure that increases irrigation efficiency, protecting a river system from being over-appropriated may require water administrators to take concrete steps to cap depletions.

However, protecting existing water rights holders against these new depletions poses special challenges. One way to deal with this challenge is to measure ET in some acceptable way, posted by the water rights administrative authority in a public place. Such a public posting could contribute to a more open and transparent understanding and distinction of water application versus water depletion. This understanding could encourage a better-informed and more professionally-implemented water administration. Growers who doubted the accuracy of the consumptive water right based on the posted ET would have the right to prove the error by their own measurements.

In May 2011, the US Supreme Court ruled on a case in which downstream water users in the state of Montana discovered that increased upstream use of center pivot irrigation in Wyoming where surface irrigation had previously occurred in the Yellowstone River system. The problem arose in the later part of the 20th century when center pivot irrigators continued to divert their historical diversions from the river, but returned less to the system because the center pivot irrigation systems raised irrigation efficiencies. The court ruled against Montana, stating that the language of the 1950 Yellowstone Compact did not prohibit upstream irrigators in Wyoming from converting to new irrigation technologies, even if the conversion reduced downstream river system flows. For the future, the distinction between diversions and depletions is likely to receive growing scrutiny as new water-sharing agreements are drafted or old ones are re-negotiated. This distinction is likely to receive more attention in river basins around the world where water sharing systems do not currently exist. Few formal water sharing systems in transboundary basins currently exist outside the western world.

4. Discussion

Regardless of whether ongoing water shortages in the American southwest and in other parts of the world point to evidence of climate warming, the need to adapt irrigation patterns to water shortages will continue to inspire economically viable measures to sustain farm income, rural livelihoods, and food security. Motivated by recent severe drought that has occurred in much of the southwestern United States, this study has analyzed vulnerability, adaptability, and economic impacts of surface water shortages and elevated groundwater salinity in a sub-basin of North America's Rio Grande. The approach used accounts for economic incentives affecting farm choices on irrigation technology, crop mix, source of water, and water use in the face of various levels of surface water shortage. Findings show that when surface water supplies are reduced, irrigation farmers shift nearly all their irrigated land in production from surface water application to aquifer pumping, despite salinity impacts on reduced crop yields produced by pumping. Farmers also shift from water-using to water-saving crops except where water using crops produce a very high income per acre (pecan orchards).

Results show that even when surface supplies fall to zero, more than 60% of base regional irrigated farm income can be maintained as long as irrigators have access to groundwater pumping at a cost of $90 per acre foot, and even when elevated salinity brought on by groundwater pumping adversely affects crop yields. That is, even when water in the checking account (river) is gone, water in the savings account (aquifer) combined with public subsidies for drip irrigation provide a valuable cushion for growers to cap income losses as they adapt to drought of greater severity.

Use of water in agriculture is perceived by wide segments of society as inefficient. Irrigated agriculture often receives intense scrutiny because it competes with other sectors for water and because of its sometimes negative impact on the environment. The pressures to become more efficient in the use of water in agriculture will increase in the future. In looking to the future, growing physical water scarcity is may be the single biggest water problem worldwide. Global food production may soon be limited by water availability, as it already is now in many geographical areas. But it will be increasingly difficult to generate additional water supplies for agriculture without harming the environment and other users of water.

Having access to a shallow aquifer, even when salinity levels are elevated at 2013 levels compared to river water, is a valuable savings account needed to sustain a difficult surface water shortage in farming. Even though the aquifer's water table is reduced after 3 years' running of aquifer depletion, it still has a considerable amount of remaining economically accessible water. With that aquifer in place, 47% of total income (62% with a 100% subsidy of drip irrigation conversions) is maintained in the extreme situation if all surface water supplies fell to zero. Without the aquifer, none of that farm income is maintained. So access to the aquifer savings account, even at a pumping cost of $90 per acre foot, is worth an estimated $13.7 million for the year 2013 ($17.9 million with the 100% drip subsidy) for New Mexico growers in the Rio Grande Project Area. These income impacts exclude all effects on the business community that trades with agricultural producers.

With the aquifer available for use by irrigated agriculture, a surprisingly small percentage of land is idled as the surface (river) water becomes scarce. Even with no drip irrigation subsidy, 73% of full water supply land stays in production as surface water supplies fall to zero, thanks to the availability of the aquifer. With a 100% subsidy, all land stays in production, because the transition to drip irrigation becomes more affordable to growers.

Farmers will convert into water conserving irrigation technologies when faced with lower financial costs for that conversion. Public subsidies for conversion from flood to drip irrigation offset many of the impacts of drought on reduced farm income. These subsidies will also raise the value of food production, reduce the amount of water applied to crops, but can increase crop water depletions. Our approach for analyzing drought adaptation impacts and adjustment strategies in the world's irrigated regions can be applied where water shortages loom, food security is important, and water conservation policies are under debate.

The most important limitations of this study center on our currently weak access to experimental data on opportunities to substitute non-water inputs for reduced water supplies in the Rio Grande Basin. For future work, we hope to be able to develop irrigated crop production functions using various kinds of experimental data. Ideally these data could come from field trials conducted at selected research stations that identify irrigated crop yields by crop, water application rate and timing, irrigation technology, water quality, location, elevation, growing season, and opportunities to substitute various non-water inputs for water. Important non-water inputs include fertilizer, herbicides, drought and salt-resistant crop varieties, labor, and capital. Results of such experimental work could contribute to improved legal structures, better irrigation infrastructure, and enhanced capacity for irrigated crop production to adapt to ongoing and recurrent drought.

Despite these limitations, this paper has attempted to make a small dent on addressing an important problem of water shortage. Motivated by ongoing water shortage in the southwestern United

States, this study has analyzed vulnerability, adaptability, and economic impacts of irrigation to shortages in a sub-basin of North America's Rio Grande. The approach used accounts for economic incentives affecting farm choices on irrigation technology, crop mix, source of water, and water use in the face of various levels of surface water shortage. Findings show that when surface water supplies are reduced, irrigation farmers shift nearly all their irrigated land in production from surface water application to aquifer pumping, despite salinity impacts on reduced crop yields produced by pumping. Our approach for analyzing drought adaptation impacts and adjustment strategies in the world's irrigated regions can be applied where water shortages loom, food security is important, and water conservation policies are under debate.

Appendix A

This documentation presents the elements of the Irrigation Water Policy Model (IWPM) developed at the New Mexico State University (USA) College of Agricultural, Consumer, and Environmental Sciences. Additional details and the model's GAMS code are posted on the web at http://agecon.nmsu.edu/fward/water/. The model and its documentation were originally developed for application to the Rio Grande Project Area in the Upper Rio Grande Basin (Fig. 1). However, it is adaptable to the hydrology, land use patterns, irrigation, economics, and institutions of any basin. The essential principle of the hydrology component of model is mass balance, both for surface and groundwater flows, water diversions and water depletions for use in irrigated agriculture.

Important variables tracked include crop mix, crop yields, land in production, and farm income associated with various public subsidies of water conserving technology under conditions of various water supply scenarios from drought and/or climate change. The model structure is defined below using the GAMS notation, described by the vendor at gams.com.

A.1. Sets

Sets are the dimensions over which the drought adaptation model is defined. A similar structure could be used for irrigated agriculture anywhere irrigation is practiced. We used the following sets and set elements.

i	resource	/land, water/
j	crop	/alfalfa, cotton, lettuce, onions, green chile, red chile, pecans/
k	technology	/flood, drip/
n	surface supply scenario – percent full	/100, 80, 60, 40, 20, 0/
s	conversion subsidy – percent capital cost	/0, 100/
w	water source	/sw (surface water), gw (groundwater)/

A.2. Data

All of the following parameter (data) terms end in _p to distinguish parameters (known terms) from unknown variables. Parameters are:

Yield_p(j,k,w)	crop yields (tons/acre)
Yield_salinity_p(j)	percentage of full yields with saline water for year 2013 (0–100)
Price_p(j,p)	crop prices ($ per ton)
Res_price_p(i,j,k,w)	resource price ($/ac-ft for water, $/acre for other inputs)
Land_tot_p(j)	base land observed in production by crop (acres)
Land_p(j,k)	land by crop and technology for base year (acres)
Tot_land_p	total land summed over crops and technologies (acres)
Bw_apply_p(j,k)	water application rate (feet depth/yr)
Bw_dep_p(j,k)	water depletion rate – ET (feet depth/yr)
Annpayment_p	annualized capital cost of converting from surface to drip system ($/ac)
subsidy_p(s)	drip irrigation subsidy proportion of annual conversion capital cost (0–100)
nres_price_p(i,j,k,s,w)	net resource price per unit adjusted by drip subsidy proportion ($/acre)
Cost_acre_p (j,k,s,w)	costs per unit land for all inputs ($/acre)
Netrev_acre_p (j,k,s,w)	net revenue per unit ($/acre)
B_0_p(j,k)	intercept in crop yield function – sets value marginal product water = price
B_1_p(j,k)	linear term in crop yield function – sets vmp water = price
RHS_wdep_p (n)	regional depletable water supplies available (ac-ft/yr)
RHS_land_p	regional irrigated land available per year (acres)

A.3. Variables (unknowns)

Each unknown variable ends in _v, to distinguish variables from known data. The model solves for the optimal value of each of these variables, for which the goal is to maximize total regional net farm income.

Yield_v (j,k,n,s,w)	yield (tons/ac)
wat_apply_v(n,s,w)	water application (ac-ft)
wat_dep_v (n,s,w)	water depletion per acre – ET – (ac-ft)
t_wat_app_v(n,s)	total water applied summed over sources (ac-ft/yr)
t_wat_dep_v(n,s)	total water depleted summed over sources (ac-ft/yr)
wat_app_ac_v(n,s)	water applications averaged over all lands (feet)
Land_v (j,k,n,s,w)	land in production (acres)
Tot_land_v(n,s)	total land in production (acres)
land_pecan_v(n,s)	total land in pecan orchard production (acres)
Grossrev_v (j,k,n,s,w)	gross revenue ($ US/acre)
Netrev_v (j,k,n,s,w)	net revenue ($ US/acre)
Income_v (n,s)	total regional farm income ($ US/year)

A.4. Equations

Several algebraic relationships characterize drought adaption by growers in the Rio Grande Project Area of New Mexico. The most important relationships deal with water applications, water depletions, land in production by crop, crop yields, and farm income.

A.4.1. Water applied

Total water applied to crop irrigation is based on the quantity of land that can afford to be brought under production. It is:

$$\text{wat\_apply\_v}(n,s,w) = \text{sum}((j,k), \text{Land\_v}(j,k,n,s,w) * \text{Bw\_apply\_p}(j,k)) \quad \text{(A1)}$$

Land_v(j,k,n,s,w) is total land brought into production for the j-th crop for the k-th resource (land and water) for the s-th subsidy irrigated by the w-th water supply source. The amount of land brought into production is based on the value of the marginal productivity of water. Marginal productivity influences farm decisions, but is rarely observed in regional average data of the sort commonly published, such as by the US land grant university extension programs. One important source of nonlinearity in the farmer's production function used in our study is heterogeneous land quality, resulting in declining yields as the total amount of land increases for a given crop planted. While declining land quality at the regional level with an expanded scale of production for any given crop simplifies the many sources of declining yields, it captures much of the farm behavioral response.

Total water applied to crops summed over all water sources, a simple accounting identity, is defined as:

$$\text{t\_wat\_app\_v}(n,s) = \text{sum}(w, \text{wat\_apply\_v}(n,s,w)) \quad \text{(A2)}$$

Water applications per acre averaged over all land in production is:

$$\text{wat\_app\_ac\_v}(n,s,) = \text{t\_wat\_app\_v}(n,s)/[1 + \text{tot\_land\_v}(n,s)] \quad \text{(A3)}$$

Data on average water applications are needed to administer water rights in New Mexico by the State Engineer's Office. Under current (2013) regulations enforced by that office, an upper bound of total water applications from all sources cannot exceed 4.5 acre feet per acre. The small constant is included in the denominator to avoid dividing by zero.

A.4.2. Water depleted

Total water depletion in the project command area is measured as:

$$\text{wat\_dep\_v}(n,s,w) = \text{sum}((j,k), \quad \text{Land\_v}(j,k,n,s,w) * \text{Bw\_dep\_p}(j,k)) \quad \text{(A4)}$$

That is, water depletions equal the amount of water depleted summed over crops and irrigation technologies. Total water depleted by crops summed over groundwater and surface water sources is:

$$\text{t\_wat\_dep\_v}(n,s) = \text{sum}(w, \text{wat\_dep\_v}(n,s,w)) \quad \text{(A5)}$$

Farmers find both surface and groundwater to be economically attractive sources of water. Groundwater typically has higher salinity content in the project area, so yields are lower because of that salinity, with onion yields in the project area especially sensitive to elevated salinity.

A.5. Land in production

Total land in production, summed over crops, technologies, and water sources is:

$$\text{Tot\_land\_v}(n,s) = \text{sum}((j,k,w), \quad \text{Land\_v}(j,k,n,s,w)) \quad \text{(A6)}$$

Total land in production for pecan orchards is:

$$\text{Land\_pecan\_v}(n,s) = \text{sum}((k,w), \quad \text{Land\_v}(\text{'pecan'},k,n,s,w)) \quad \text{(A7)}$$

Land planted to pecan orchards is a high income long term investment that is slow to mature (greater than seven years). Land in pecan orchards is constrained below to never fall below base levels (23,000 acres in 2013). This constraint reflects the lucrative economic profitability that would be lost for future years if inadequate quantities of water are applied to those orchards in the current year. No matter how low the river (checking account) runs, water will be brought to those orchards if at all possible, for example by pumping the aquifer or purchasing pumped water from growers of other crops.

A.5.1. Crop yields

Observed crop yields supplied with surface water are reduced with expanded acreage, based on the principle of Ricardian rent. The equation below uses positive mathematical programming to assure that small changes in water supply scenarios or small policy changes produce small results. This method assures a continuous mapping from small changes in drought levels or small changes in irrigation policies for adapting to drought or climate into small changes in results (yields in this case).

$$\text{Yield\_sw\_v}(j,k,n,s) = B_0\text{\_p}(j,k) + B_1\text{\_p}(j,k) * \text{sum}(w, \text{Land\_v}(j,k,n,s,w)) \quad \text{(A8)}$$

This equation specifies a surface irrigated crop yield function with decreasing yields in the face of greater amounts of land in production for any given crop and irrigation technology. Yields for surface water irrigation decline for any given crop, irrigation technology, water supply scenario, and subsidy level as the scale of land under irrigation expands.

Decreasing yields that occur in the face of an expanded scale of land in production would occur because there has never been complete specialization in any crop at the regional level. Complete specialization is rarely observed in irrigated areas with large amounts of land in production at the regional level. One farm manager may specialize in a single crop using one irrigation technology, but at a regional level, complete specialization is rare. The declining yield function allows calculation of the parameters B_0_p(j,k) and B_1_p(j,k) observed under base conditions, in which there is no surface water drought and no irrigation conversion subsidies. Under these observed conditions, the value of the marginal product of water is set equal to its price per acre foot applied. More mathematical details, for the patient reader, are described in Dagnino and Ward, (2012).

Available data commonly show the ratio of water to land to be fixed for any given irrigation technology, crop, and location. It is most common to observe data on actual yields and on the amount of water and other inputs. This observation reveals only one point on the production function. The crop water production function in (A8) shows each crop's yield falling as more land is planted to that crop. Declining yields with an expanded scale of production occur because each crop's best lands are used first, after which yields decline.

Salinity reduces crop yields. Yields from crops irrigated by groundwater pumping are lower than surface yields. Yields with saline water (2013 salinity levels) range from 75% to 90% of surface water yields irrigated with sweet water, as described below:

$$\text{Yield\_gw\_v}(j,k,n,s) = \text{Yield\_salinity\_p}(j) * \text{Yield\_v}(j,k,n,s,\text{'sw'}) \quad \text{(A9)}$$

A.5.2. Income

Observed gross revenue per acre in production equals price times yield:

$$\text{Grossrev\_v}(j,k,n,s,w) = \text{Price\_p}(j) * \text{Yield\_v}(j,k,n,s,w) \quad \text{(A10)}$$

Observed net revenue per acre equals price multiplied by yield minus costs of production including all water costs, equal to:

$$\text{Netrev\_v}(j,k,n,s,w) = \text{Price\_p}(j) * \text{Yield\_v}(j,k,n,s,w) - \text{Cost\_acre\_p}(j,k,s,w) \quad \text{(A11)}$$

In (A11), any crop's yields decline with an expanded scale of land in production.

Farm income is measured as:

$$\text{Income\_v}(n,s) = \text{sum}((j,k,w), \quad \text{Land\_v}(j,k,n,s,w) * \text{Netrev\_v}(j,k,n,s,w)) \quad \text{(A12)}$$

That is, total farm income for the project service area is land in production multiplied by net revenue per unit land.

A.6. Bounds

Several bounds are established to assure that the model replicates real world data, technology, and farm behavior, while also producing realistic responses to future climate or policy adaptations to climate.

A.6.1. Water applied

In the Rio Grande Project Area, the New Mexico State Engineer's office limits total water applications to 4.5 acre feet per acre, summed over all sources (surface water and groundwater). The total is a weighted average over all lands in production, requiring an upper bound on average water applications:

$$\text{wat\_app\_ac\_v.up}(n,s) = 4.5 \quad \text{(A13)}$$

The term .up, protects the regional average of water applications from exceeding its upper bound.

Total surface water available for application is defined by a given year's runoff combined with an interstate water sharing institution known locally as the Rio Grande Compact. This interstate compact defines how headwater surface river flows are shared among the three US states of Colorado, New Mexico, and Texas.

$$\text{wat\_apply\_v.up}(n,s,\text{'sw'}) = \text{RHS\_wapply\_p}(n) \quad \text{(A14)}$$

This upper bound enables the model to be run under a range of water supply shortages from a full supply to an extreme drought of zero surface water supplies.

A.6.2. Water depleted

An upper bound on total surface water depletions is set to:

$$\text{wat\_dep\_v.up}(n,s,\text{'sw'}) = \text{RHS\_wdep\_p}(n) \quad \text{(A15)}$$

This upper bound is established as a measure to protect senior water right holders, when drip irrigation is brought into production for which depletions are typically higher than those produced by flood irrigation. Groundwater pumping is not directly regulated beyond the 4.5 acre feet per acre of total use described above. It is typically limited more by the cost of pumping and by salinity that reduces crop yields. However protecting existing water right holders requires limiting regional depletions by groundwater pumping from increasing in the face of a flood to drip conversion subsidy.

A.6.3. Land in production

Total land in production cannot exceed base acreage, about 90,000 acres. For the current study, data were available for only about 2/3 of that land.

$$\text{tot\_land\_v.up}(n,s) = 90{,}000 \quad \text{(A16)}$$

The equation below states that total land in pecan production cannot fall below base observed levels (23,000 acres) because of the very high financial cost faced by growers who would lose a pecan orchard. This requirement is shown by establishing a lower bound on pecan production (.lo). A more sophisticated dynamic model would calculate the loss in pecan orchards and a comparison of discounted net present value of income that would occur with and without irrigation.

$$\text{land\_pecan\_v.lo}(n,s) = 23{,}000 \quad \text{(A17)}$$

There is no drip irrigation possible under surface irrigation when surface supplies falls below 40% of their full supply. This requirement occurs is because the canals have too little water in them to be reliable as a source for drip irrigation. This limitation is expressed as the following two equations:

$$\text{Land\_v.fx}(j,\text{'drip'},\text{'20\_pct'},s,\text{'sw'}) = 0 \quad \text{(A18)}$$

$$\text{Land\_v.fx}(j,\text{'drip'},\text{'00\_pct'},s,\text{'sw'}) = 0 \quad \text{(A19)}$$

A.7. Objective

The objective is to maximize total regional farm income by maximizing Eq. (A12) for each water supply scenario (p index) and irrigation technology conversion subsidy (s index). It achieves this maximization by seeking and finding the income-maximizing quantity of land and associated water by crop (j), irrigation technology (k), and source of water (w).

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