[Online Appendix for "Droughts, deluges, and (river) diversions: Valuing market-based water reallocation," by Will Rafey]

A Estimation details

A.1 Concentration algorithm

I concentrate out ψ_c with the following procedure of Ackerberg *et al.* (2015, Appendix A4). For a candidate $\tilde{\theta}_c$, construct the residuals with (15) as

$$\hat{\omega}_{ict} = \hat{\Phi}_{ict} - \tilde{f}_c(W_{ict}, X_{ict}, K_{ict}, R_{ict}) \tag{A1}$$

and

$$\hat{\omega}_{ic,t-1} = \hat{\Phi}_{ic,t-1} - \tilde{f}_c(W_{ic,t-1}, X_{ic,t-1}, K_{ic,t-1}, R_{ic,t-1}) \tag{A2}$$

and regress (A1) against (A2). The coefficients of this regression give the transition function ψ_{ct}. The residual of this regression,

$$\tilde{\xi}_{ict} \equiv \omega_{ict} - \hat{\psi}_{ct}(\omega_{ic,t-1}) + \varepsilon_{ict}$$

is then stacked over t as $m_{ic} = (\tilde{\xi}_{ic1} \ldots \tilde{\xi}_{icT})'$ to form the instrumental variables estimator

$$(\hat{\theta}_c, \hat{\psi}_c) \in \arg \min_{(\tilde{\theta}_c, \tilde{\psi}_c)} \left[\sum_i \mathbf{Z}'_{ic} m_{ic}(\tilde{\theta}_c, \tilde{\psi}_c)\right]' \widehat{\Xi} \left[\sum_i \mathbf{Z}'_{ic} m_{ic}(\tilde{\theta}_c, \tilde{\psi}_c)\right], \tag{A3}$$

The estimator (A3) is consistent for (θ_c, ψ_c) under that standard rank assumption that the inverse of $\mathbb{E}\left[\mathbf{Z}'_{ic} \frac{\partial m_{ic}}{\partial(\theta_c, \psi_c)}\right]$ exists for each c and every i. I recover the weight matrix $\widehat{\Xi}$ using a two-step procedure that first estimates (A3) with $\widehat{\Xi} = I$ to obtain $(\check{\theta}_c, \check{\psi}_c)$ as above, then lets $\check{u}_{ic} = q_{ic} - \check{f}_c - \check{\psi}_{ic}$ and re-estimates (A3) with $\widehat{\Xi} = [\sum_i \mathbf{Z}'_{ic} \check{u}_{ic} \check{u}'_{ic} \mathbf{Z}_{ic}]^{-1}$.

To recover $\{\hat{\omega}_{ict}\}$ for farm-years not in the main estimation sample, i.e., all (i, t) such that i first appears in the sample in year t (see Appendix B), I re-estimate the polynomial series Φ_{ict} over all farms and use the coefficients of $F_c(\cdot)$ from the estimation sample to recover $\hat{\omega}_{ict} = \widehat{\Phi}_{ict} - \hat{f}_c(\cdot)$.

A.2 Common water-augmenting technical change

Exogenous water-augmenting technical change that is common across farms and takes a known form can be included directly in the production function. I denote water-augmenting technical change by ζ_{ict} and consider the augmented production function

$$F_c(\cdot, \zeta_{ict}) = \left[\alpha_c \left(e^{\zeta_{ict}} W_{ict} + \vartheta_c R_{ict}\right)^{\frac{\sigma_c - 1}{\sigma_c}} + (1 - \alpha_c) K_{ict}^{\frac{\sigma_c - 1}{\sigma_c}}\right]^{\frac{\sigma_c}{\sigma_c - 1}\beta_{cW}} \prod_j (X^j_{ict})^{\beta_{cj}}. \tag{2'}$$

I consider irrigation-specific technical change that varies across two observables. First, over time, using the panel structure of the data; second, over observed irrigation equipment, using a measure of farm-specific irrigation capital contained in the data.

Technical change over time. I let water-augmenting technical change depend only on c and t, defined as

$$\zeta_{ict} = \mathbf{1}_{t\in T_0} + \zeta_{c1}\mathbf{1}_{t\in T_1} + \zeta_{c2}\mathbf{1}_{t\in T_2} \tag{A4}$$

where $\{T_\tau\}$ is a partition of 2007–2015 into three periods of equal length. This requires no revision of χ_{ct} in (6), which already depends on t.

Observable irrigation equipment The data includes a direct value of irrigation equipment owned by the farm, K^I_{it}. All farms have land equipped for irrigation, primarily using flood-and-furrow methods; 46.9% of farms report some additional irrigation equipment of nonzero value. Relative to a farm's total capital, the value of this irrigation equipment is small—\$47,629 for an average farm with irrigation equipment—comprising 0.55% of non-land accounting capital for the median farm that does have nonzero irrigation equipment and 1.69% of non-land capital for the 75%-ile such farm. If irrigation equipment adoption decisions are exogenous,[1] then it is straightforward to allow the 47% of farms with nonzero irrigation equipment to have different water-augmenting technology, so that

$$\zeta_{ict} = 1 + \zeta_c \mathbf{1}\{K^I_{it} > 0\}. \tag{A5}$$

Then I estimate F_c, now including ζ, as before, adding an indicator for irrigation equipment, $\mathbf{1}\{K^I_{it} > 0\}$ to the information set $\mathcal{F}_{i,t-1}$ in the exclusion restriction (10), and extending the functions for materials demand and the productivity control to include $\mathbf{1}\{K^I_{it} > 0\}$ as an argument in (6) and (15).

B Details of data construction

B.1 Agricultural production

1. Sample restrictions

1.1 Geographic restrictions. The survey collected data from the following regions from 2007–2015 in the southern Murray Darling Basin: Victoria Murray, Victoria Goulburn, South Australia Murray, New South Wales Murrumbidgee, and New South Wales Murray. (Survey regions outside of these five sMDB regions were discontinued after 2011 due to funding cuts.) Australian fiscal years run 1 July to 30 June; throughout, "2007" refers to 1 July 2006 to 30 June 2007, et cetera.

1.2 The rotating survey design means not all farms are observed more than once. I restrict estimation of (θ, ψ) to farms observed in at least two years. Counterfactuals are calculated with data from all farms.

2. Variable definitions

2.1 Output, Q_{ict}, is computed for each crop type c as the weighted sum of physical production Q_{ic_kt} over all crops $c_k \in c$,

$$Q_{ict} = \sum_{c_k\in c} P_{c_k 0} Q_{ic_k t}$$

[1] This is partially motivated by the fact that during my period, the government ran a large-scale subsidy program irrigation technology, which complicates modeling the adoption decision.

weighted by baseline average prices, $P_{c_k0} \equiv \sum_i Y_{ic_k2007} / \sum_i Q^{\text{sold}}_{ic_k,2007}$, where Y_{ic_k2007} is the recorded revenue (AUD) farm i received in 2007 for $Q^{\text{sold}}_{ic_k,2007}$ tonnes of crop c_k sold. The categories are:

For $c =$ annual irrigated, $c_k \in$ {rice, oilseeds, cotton, pulse, vegetables, cereal, coarse grains}.

For $c =$ annual nonirrigated, $c_k \in$ {rice, oilseeds, cotton, pulse, vegetables, cereal, coarse grains}.

For $c =$ horticulture, $c_k \in$ {pome fruits, citrus fruits, stone fruits, vine fruits, wine}.

For $c =$ dairy, c_k corresponds to milk production (liters).

2.2 Crop prices. I define crop-type prices as the weighted sum of the value of c_k in year t, $P_{c_kt} \equiv \sum_i Y_{ic_kt} / \sum_i Q^{\text{sold}}_{ic_kt}$ in year t for crop c_k, divided by output,

$$P_{ict} = \frac{\sum_{c_k \in c} P_{c_kt} Q_{ic_kt}}{\sum_{c_k \in c} P_{c_k0} Q_{ic_kt}}.$$

2.3 Irrigation volumes and extent of land planted are recorded at the resolution W_{ic_kt} and K_{ic_kt}, so $W_{ict} \equiv \sum_{c_k \in c} W_{ic_kt}$ and $K_{ict} \equiv \sum_{c_k \in c} K_{ic_kt}$. Irrigation and land for dairy is the sum of irrigation and land used for pasture to grow feed.

Other inputs

2.4 Materials, X^M_{ict}, are calculated as the sum of i's year-t expenditure on crop and pasture chemicals, fertilizer, seed, electricity, fuel, packing materials, and packing charges. The survey also records expenses for repairs and maintenance, administrative costs, motor vehicle expenses, handling and market expenses, and other services.

2.5 Labor, X^L_{ict}, is measured in total weeks worked, both by hired labor and family labor.

2.6 The wage, $P^L_{X,it}$, is the sum of i's hired labor costs and imputed family labor costs in year t (AUD), divided by the total labor weeks worked on farm i in year t.

2.7 Farm-level financial capital, which sums the value of land owned, equipment, water rights, livestock, and other capital, is also recorded. I do not use this financial measure for data quality concerns. First, it includes two forms of capital already accounted for directly in physical units (land and dairy cows). Second, farms may rent machinery and equipment owned by others. Third, the approach I take to assign inputs recorded at the farm level to crop types relies on static first-order conditions inappropriate for dynamic fixed factors. The inclusion of this financial variable in the production function does not substantively affect results; the coefficient estimated is, in most cases, close to zero.

Environmental variables

3.1 Rainfall is collected by the BoM, interpolated to a grid of 0.05 degree resolution. Rainfall is matched to farms by ABARES analysts with GIS codes. Winter rainfall is April–October and summer rainfall is November–March.

3.2 Evapotranspiration. Discussed at greater length below.

Other prices

4. Average farm interest rate data collected by ABARES. Real interest rate calculated by deflating the average nominal rate (0.0714) with the Australian Bureau of Statistics consumer

price index.

B.2 Regulatory and water market data

1. I use records of total water entitlements and annual allocations, from the New South Wales Office of Water, Victorian Water Register, and the South Australian Department of Environment, Water and Natural Resources, collated by Hughes *et al.* (2016b, pp. 45–46).

2. I obtain market-level records of the price, volume, date, and origin- and destination-region for every water trade between 2008–2015, from the Murray-Darling Basin Authority and the now-defunct National Water Commission.

For 2007, which predates federal reporting requirements, I compile price data from various state government registries and a private broker.

B.3 Evapotranspiration

As discussed in Section 2.2, I follow the modern approach to calculating crop-specific evapotranspiration, the FAO56 method for calibrating the Penman-Monteith equation (Allen *et al.*, 1998). This involves three steps.

1. First, various local environmental factors affect a plant's natural water demand over time. In the Penman-Monteith approach, these conditions are captured by a measure of "reference evapotranspiration," $E^0_{i\tau}$ at some time τ and location i. I obtain local measures of reference evapotranspiration from the Australian Bureau of Meteorology (Webb, 2010), interpolated to the same 0.05 degree grid as rainfall. These measures are derived from the BoM Australian Water Resource Assessment Landscape (AWRA-L) model (Frost *et al.*, 2016) based on local soil data and daily rainfall, temperature, humidity, wind, and solar radiation.

2. Second, a given crop's water requirements will change over time through the growing cycle. I obtain crop development stages from Allen *et al.* (1998, Table 11) and planting times from various Australian agricultural industry sources, summarized in Table A4. This information allows me to construct a calendar for Australian crop seasons for each of the twelve crops. The calendar indicates the typical months of the growing cycle, divided into four periods: initial growth, early development, maturity, and harvest. For each crop c_k, this delivers a set of weights $\{\gamma^j_{c_k,m}\}^{12}_{m=1}$ for each growing period $j \in \{\text{initial}, \text{dev}, \text{mid}, \text{harvest}\}$ that equal 1 if crop c_k is typically in development stage j in month m, and zero otherwise.

3. Third, environmental factors affect crop water demand through the growing cycle differentially across crops. The standard approach to adjust for these differences is to use crop coefficients derived from agronomic studies. I therefore obtain crop coefficients, $\kappa^j_{c_k}$ for each crop type c_k and each of its growing periods j, from Allen *et al.* (1998, Ch. 6, Table 12).

4. These three details allow me to calculate the effective evapotranspiration for each crop in a location (farm) in a given year. The measure of total evapotranspiration for farm i growing crop type c_k in year t is

$$E_{ic_kt} = \sum_{m=1}^{12} \sum_j \kappa^j_{c_k} \gamma^j_{c_k,m} E^0_{im} \tag{A6}$$

where $E^0_{im} = \sum_{\tau \in m} E^0_{i\tau}$ is the total monthly reference evapotranspiration for month m. Equation (A6) corresponds to crop evapotranspiration under standard conditions, for "crops grown in large fields under excellent agronomic and soil water conditions" (Allen *et al.*, 1998).

5. I then incorporate these evapotranspiration measures into the model of annual irrigated agricultural production by defining production as a function of irrigation and effective rainfall (rainfall "net of evapotranspiration"). To construct the measure of effective annual rainfall, I take the monthly values of $E_{ic_k m}$, and calculate monthly rainfall constrained by crop evapotranspiration, so that

$$R_{ic_k t} = E^R_{ic_k t} - E^V_{ic_k t} = \sum_{m \in t} \min\{\text{rain}_{ic_k m}, E_{ic_k m}\},$$

so that rainfall matters for production (only) up to the crop water requirements each month. This approximation excludes rainfall occurring outside of the relevant growing season (since $\gamma^j_{c_k,m} = 0$) as well as rainfall that occurs in excess of the predicted crop water requirements. It also allows rainfall to matter more in cases in which particularly hot temperatures with high rates of evapotranspiration than in cases where low rates of evapotranspiration make rainfall less useful.

6. Lastly, I convert this measure to volumetric terms and aggregate over the crops in each crop type, so that $R_{ic_k t} = \sum_{c_k \in c} K_{ic_k t} R_{ic_k t}$.

B.4 Estimate of global water trade

The denominator is calculated with freshwater withdrawals for 177 countries over 2000–2016, which equal 3.729 billion ML per year (FAO, 2016).

The numerator is based on my estimates of upper bounds for water reallocation in countries that, to my knowledge, have active water markets. I take 50% for Australia; 5% for the U.S. (from 2–4% in Schwabe *et al.*, 2020 for the western United States); 10% for Chile (from 5.6% in Hearne and Donoso, 2014, p. 121); and 1% for Spain (Rey *et al.*, 2014, p. 128).

Using these weights, and withdrawals for each of these countries from FAO (2016), I obtain

$$\frac{0.357 \times 10^9 \text{ML}}{3.729 \times 10^9 \text{ML}} = 0.0096.$$

Note that this calculation excludes groundwater markets in China (Wang *et al.*, 2014) and India (Saleth, 2014), which are informal, localized, and largely unregulated.

References for Online Appendices A–B

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A Supplementary Tables (Not For Publication)

Table A1. Yields, Irrigation, and Rainfall

A. Yields, ('1000 AUD/ha)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2007–15
Perennial	9.79	10.93	11.81	10.31	11.27	8.99	13.63	13.83	15.14	11.26
Annual (irrigated)	4.74	7.21	7.45	4.79	4.98	2.42	8.51	4.83	5.06	4.98
Annual (nonirrigated)	0.23	0.48	0.19	0.20	0.61	0.49	0.23	0.54	0.61	0.40
Pasture	5.70	8.34	8.46	7.26	5.53	4.60	3.20	4.65	9.28	6.32

B. Irrigation, (ML/ha)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2007–15
Perennial	6.28	5.66	5.32	5.42	4.67	5.56	6.85	5.87	5.86	5.73
Annual (irrigated)	4.25	3.72	3.67	5.25	6.43	6.41	4.27	9.30	6.85	5.75
Annual (nonirrigated)	0	0	0	0	0	0	0	0	0	0
Pasture	2.96	2.64	2.39	2.21	2.43	2.81	2.82	3.58	3.39	2.78

C. Rainfall and Evapotranspiration (mm)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2007–15
Summer rainfall (mm)	98.5	166.4	137.5	236.2	418.3	343.3	85.8	149.6	150.4	203.6
(standard deviation)	24.6	92.4	48.3	63.4	77.1	106.5	41.1	38.0	59.2	127.4
Winter (mm)	122.8	151.4	154.3	212.4	356.6	193.7	173.0	222.4	249.8	200.1
(standard deviation)	33.9	76.6	73.4	89.0	89.0	64.8	65.3	89.2	90.6	102.9
Annual (mm)	221.3	317.8	291.8	448.7	774.9	537.0	258.7	372.0	400.2	403.6
(standard deviation)	52.2	158.3	112.8	140.8	154.4	164.4	104.6	118.9	143.3	213.8
Effective rainfall (mm)	142.4	183.5	183.6	256.1	387.4	280.6	128.2	199.9	198.5	221.2
(standard deviation)	58.3	92.7	69.3	79.0	98.9	83.1	45.1	53.8	79.9	108.6

The unit of observation is (i, c, t) for Panels A–C. Appendix B defines perennial, annual, and pasture crops. Winter rainfall is April–October and summer rainfall is November–March. Effective rainfall adjusts for derived crop evapotranspiration as detailed in Appendix B.

Source: ABARES Survey of Irrigated Farms; Australian Bureau of Meteorology; author's calculations.

Table A2. Output, Land, Labor, Materials

	$N \times T$	mean	s.d.	Q.10	Q.25	Q.50	Q.75	Q.90
price-weighted quantity	2,059	971.46	1,421.07	43.30	117.54	406.89	1,259.50	2,602.15
revenue	2,059	680.98	990.12	43.13	118.27	345.26	910.22	1,702.58
crop price index	2,059	0.89	0.30	0.43	0.68	0.94	1.11	1.23
irrigated land, hectares	2,059	296.17	519.86	11.40	24.35	100	351.50	778.40
land operated, hectares	2,059	563.00	1,142.37	16.20	38.40	189	595.50	1,359.20
labor, weeks	2,059	178.60	282.50	43	69.75	114.47	190	325.20
materials	2,059	132.85	217.23	10.83	23.94	65.08	150.80	310.16

Farm-level input-output data. Units are in thousands of 2015 Australian dollars.

Source: ABARES Survey of Irrigated Farms.

Table A3. Regional Water-Sharing Rules

	2007	2008	2009	2010	2011	2012	2013	2014	2015
NSW Murray	0.095	0.059	0.179	0.351	0.735	0.433	0.685	0.965	0.652
NSW Murrumbidgee	0.247	0.229	0.316	0.368	0.767	0.764	0.754	0.664	0.582
SA Murray	0.800	0.320	0.180	0.620	0.670	1	1	1	1
VIC Goulburn	0.290	0.570	0.330	0.720	1.014	1.014	1.014	1.014	1.014
VIC Murray	0.950	0.430	0.350	1.000	1.015	1.015	1.015	1.015	1.053

Data underlying Figure A1. Total water allocated in each region and each year, as a fraction of total entitlements on issue at baseline, 2007.

Source: NSW, VIC, and South Australia state government regulatory records.

Table A4. Intraday Water Price Dispersion

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	Days	Volume
VIC Murray	0	0.043	0.076	0.124	0.140	2.471	1,908	2,217,989
NSW Murray	0	0.019	0.058	0.123	0.147	1.311	1,907	2,569,916
SA Murray	0	0.018	0.051	0.127	0.114	3.347	643	706,268
Murrumbidgee	0	0.032	0.073	0.173	0.173	2.552	1,211	2,283,161
Goulburn	0	0.029	0.058	0.117	0.116	4.217	1,681	1,650,034
All regions	0	0.068	0.126	0.213	0.239	4.345	2,459	9,427,368

Summary of the daily volume-weighted coefficients of variation for water prices, over all days with at least two trades (2008–2015). The last two columns report the number of days with at least two trades and total volume of traded water (ML), respectively. Constructed from transaction-level water price data from the annual allocation market described in Table 1.

Source: MDBA administrative transaction-level water price data.

Table A5. Growing Calendars and Crop Coefficients

	init	dev	mid	late	plant	source
Perennial crops						
citrus	30	50	130	30	September	FAO Table 11(n), "deciduous orchard, Calif."
citrus	60	90	120	95	September	FAO Table 11(n), "citrus, Mediterranean"
stone fruits	30	50	130	30	September	FAO Table 11(n), "deciduous orchard, Calif."
vine	20	50	75	60	September	FAO Table 11(m), "table and raisin grapes"
wine	20	50	75	60	September	FAO Table 11(m), "wine grapes"
Annual crops						
rice		30	120	90	October	USDA IPAD, "NSW/Victoria rice"
oilseed		45	45	120	April	Australian Oilseeds Federation
cotton		60	90	120	October	USDA IPAD, "NSW/Victoria cotton"
pulse		30	120	90	October	NSW Department of Primary Industries
vegetables	30	40	40	25	September	FAO Table 11(b), "tomato"
cereal		90	130	80	April	USDA IPAD, "NSW/Victoria wheat"
coarse grains		120	30	150	September	USDA IPAD, "NSW/Victoria corn and millet"
Dairy						
feed	10	20	20	10	September	FAO Table 11(j), "alfafa, Calif."
pasture	10	80	80	80	March	FAO Table 11(j), "extensive grazing pasture"

	κ_c^{init}	κ_c^{dev}	κ_c^{mid}	κ_c^{late}	source
Perennial crops					
citrus	0.59	0.59	1.07	0.81	FAO Table 12(n), "apples, cherries, pears"
citrus	0.71	0.71	0.68	0.72	FAO Table 12(n), "citrus"
stone fruits	0.58	0.58	1.02	0.76	FAO Table 12(n), "apricots, peaches, stone fruit"
vine	0.3	0.3	0.85	0.45	FAO Table 12(m), "table and raisin grapes"
wine	0.3	0.3	0.7	0.45	FAO Table 12(m), "wine grapes"
Annual crops					
rice	1.05	1.05	1.2	0.75	FAO Table 12(i), "rice"
oilseed	0.35	0.35	1.15	0.35	FAO Table 12(h) "oil crops"
cotton	1.18	1.18	0.6	1.35	FAO Table 12(g), "cotton"
pulse	0.3	0.3	1.15	0.55	FAO Table 12(e) "legumes"
vegetables	0.7	0.7	1.05	0.95	FAO Table 12(a), "small vegetables"
cereal	0.3	0.3	1.15	0.4	FAO Table 12(i), "cereals"
coarse grains	0.3	0.3	1.15	0.4	FAO Table 12(i), "cereals"
Dairy					
feed	0.4	0.4	0.95	0.9	FAO Table 12(j), "alfafa hay"
pasture	0.3	0.3	0.75	0.75	FAO Table 12(j), "extensive grazing pasture"

Details of growing seasons and crop coefficients used to obtain evapotranspiration to construct effective rainfall. Growing season lengths reported in days and plant dates adjusted to the southern hemisphere where applicable. "FAO Tables 11–12" from Allen *et al.* (1998, Ch. 6). "USDA IPAD" from U.S. Department of Agriculture International Production Assessment Division ("Crop Calendars for Australia," `https://ipad.fas.usda.gov/rssiws/al/crop_calendar/as.aspx`).

Table A6. Water Trading and Fixed Characteristics

	Annual Rights		*Permanent Rights*	
	Buy	Sell	Buy	Sell
	(1)	(2)	(3)	(4)
$\ln(\text{net\_rainfall}_{ict})$	−0.060	0.031	0.054	0.010
	(0.028)	(0.023)	(0.027)	(0.032)
$\mathbf{1}(c = \text{annual\_nonirrig})$	−0.151	0.069	−0.034	0.009
	(0.030)	(0.025)	(0.029)	(0.036)
$\mathbf{1}(c = \text{pasture})$	−0.013	0.021	0.042	−0.031
	(0.034)	(0.029)	(0.033)	(0.040)
$\mathbf{1}(c = \text{perennial})$	−0.099	0.159	−0.016	−0.047
	(0.027)	(0.023)	(0.027)	(0.033)
$\mathbf{1}(t = 2008)$	0.166	−0.006		
	(0.034)	(0.028)		
$\mathbf{1}(t = 2009)$	0.111	0.050	−0.088	−0.322
	(0.034)	(0.029)	(0.031)	(0.038)
$\mathbf{1}(t = 2010)$	0.042	−0.079	−0.184	−0.419
	(0.038)	(0.032)	(0.032)	(0.039)
$\mathbf{1}(t = 2011)$	−0.117	−0.183	−0.177	−0.430
	(0.044)	(0.037)	(0.037)	(0.045)
$\mathbf{1}(t = 2012)$	−0.072	−0.157	−0.195	−0.380
	(0.039)	(0.033)	(0.034)	(0.041)
$\mathbf{1}(t = 2013)$	0.068	−0.010	−0.168	−0.470
	(0.051)	(0.042)	(0.041)	(0.050)
$\mathbf{1}(t = 2014)$	0.167	−0.025	−0.109	−0.266
	(0.040)	(0.033)	(0.039)	(0.047)
$\mathbf{1}(t = 2015)$	0.050	0.007	−0.171	−0.422
	(0.036)	(0.030)	(0.033)	(0.040)
$\mathbf{1}(i \in r = \text{NSW Murrumbidgee})$	−0.110	0.091	0.027	−0.022
	(0.028)	(0.023)	(0.026)	(0.032)
$\mathbf{1}(i \in r = \text{SA Murray})$	0.107	−0.180	0.039	−0.003
	(0.033)	(0.028)	(0.031)	(0.037)
$\mathbf{1}(i \in r = \text{VIC Goulburn})$	0.024	−0.105	−0.039	0.031
	(0.032)	(0.027)	(0.031)	(0.037)
$\mathbf{1}(i \in r = \text{VIC Murray})$	−0.061	−0.096	−0.002	−0.014
	(0.034)	(0.029)	(0.033)	(0.040)
Constant	0.692	0.025	−0.067	0.470
	(0.141)	(0.117)	(0.139)	(0.169)
Mean of dep. var.	0.326	0.19	0.088	0.156
Observations	2,437	2,437	1,142	1,142
R^2	0.102	0.114	0.056	0.153

Unit of observation is the farm-crop-year. OLS regression of an indicator variable for farm i
(1) buying water allocations in year t,
(2) selling water allocations in year t,
(3) increasing water entitlements owned from $t-1$ to t
(4) reducing water entitlements owned from $t-1$ to t.
Omitted factors are $\mathbf{1}\{c = \text{annual irrigated}\}$, $\mathbf{1}\{t = 2007\}$, and $\mathbf{1}\{i \in \text{NSW Murray}\}$. Conventional standard errors in parentheses.

Table A7. Productivity Estimates

	Perennial (1)	Annual irrigated (2)	Annual nonirrigated (3)	Dairy (4)
Median productivity	7.06	2.21	1.73	5.53
	(0.58)	(1.16)	(0.76)	(0.63)
Interquartile interval	[6.79,7.32]	[1.78,2.70]	[1.15,2.29]	[5.36,5.71]
range	0.53	0.92	1.14	0.35
	(0.06)	(0.15)	(0.12)	(0.04)
Interdecile interval	[6.55,7.57]	[1.47,3.06]	[0.58,2.76]	[5.19,6.02]
range	1.02	1.59	2.18	0.83
	(0.09)	(0.20)	(0.18)	(0.06)
Persistence, $\hat{\varrho}_c$	0.630	0.432	0.658	0.324
	(0.058)	(0.083)	(0.051)	(0.069)
Growth rate	0.070	0.056	0.231	-0.101
	(0.016)	(0.055)	(0.040)	(0.024)
Observations	510	170	208	254

Estimated productivities $\{\hat{\omega}_{ict}\}$, denominated in natural logarithms of AUD and recovered as $\hat{\Phi}_{ict} - \hat{f}_{ict}$, using production function estimates $\hat{F}_c$ reported in Table 3.

Persistence is defined as the coefficient $\hat{\varrho}_c$ in the regression $\hat{\omega}_{ict} = \varrho_{0c} + \varrho_c \hat{\omega}_{ic,t-1} + \varepsilon_{ict}$. Growth rate is annual and defined as $\frac{1}{NT} \sum_{i,t} (\hat{\omega}_{ict} - \hat{\omega}_{ic,t-1})$

Standard errors block-bootstrapped at the farm level (5000 iterations) in parentheses..

Table A8. Productivity Estimates: Single vs. Multi-crop Farms

	$N \times T$	mean	sd	q10	q25	q50	q75	q90
Perennial farms, single crop	894	6.989	0.408	6.523	6.733	6.974	7.247	7.505
Perennial farms, multicrop	145	6.994	0.396	6.543	6.705	7.005	7.227	7.478
Annual irrigated farms, single crop	136	2.171	0.806	1.163	1.691	2.260	2.609	3.281
Annual irrigated farms, multi crop	318	2.170	0.692	1.407	1.735	2.143	2.578	3.020
Dairy farms, single crop	322	5.653	0.402	5.206	5.393	5.585	5.863	6.157
Dairy farms, multicrop	145	5.672	0.424	5.197	5.365	5.610	5.942	6.260

Estimated productivity distributions, $\{\hat{\omega}_{ict}\}$ from Table A7, for farms producing one crop-type ("single-crop") and farms producing two or more crop-types ("multi-crop").

Table A9. Water Shadow Values at Observed Inputs

	Perennial (1)	Annual irrigated (2)	Annual nonirrigated (3)	Dairy (4)	Water market (5)
Median shadow value (AUD/ML)	399.4	79.8	24.3	272.6	160.3
	(64.3)	(14.7)	(6.6)	(90.0)	(198.9)
Interquartile interval	[281.8,649.9]	[52.8,193.0]	[14.0,42.0]	[212.9,350.2]	[55.0, 338.7]
Range	368.1	140.2	28.0	137.3	283.7
	(74.7)	(115.1)	(7.1)	(61.1)	
Interdecile interval	[226.0,978.2]	[36.2,730.9]	[9.0,59.0]	[176.8,494.8]	[24.6, 621.9]
Range	752.2	694.7	50.0	318.0	597.4
	(164.3)	(177.9)	(14.1)	(132.9)	
Observations	510	170	208	254	2,059

Water shadow water values pooled over 2007–2015, in columns (1)–(4); regional water allocation prices distributed over farms in column (5). Shadow values obtained by evaluating (14) at observed input levels, using the estimated production functions (Table 3) and productivities (Table A7).

Standard errors block-bootstrapped at the farm level (5000 iterations) in parentheses..

Table A10. Sensitivity to Technical Change: Perennial Irrigated

	(1)	(2)	(3)	(4)	(5)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.246	0.259	0.231	0.253	0.202
	(0.040)	(0.064)	(0.059)	(0.038)	(0.039)
$\frac{\partial f_c}{\partial w}$_10	0.141	0.162	0.132	0.141	0.132
	(0.028)	(0.042)	(0.040)	(0.029)	(0.039)
$\frac{\partial f_c}{\partial w}$_25	0.207	0.225	0.194	0.206	0.176
	(0.035)	(0.058)	(0.051)	(0.033)	(0.037)
$\frac{\partial f_c}{\partial w}$_75	0.301	0.309	0.282	0.319	0.243
	(0.048)	(0.075)	(0.072)	(0.047)	(0.045)
$\frac{\partial f_c}{\partial w}$_90	0.326	0.329	0.301	0.341	0.266
	(0.052)	(0.081)	(0.075)	(0.051)	(0.046)
Rainwater coefficient, ϑ_c	1.081	0.849	1.082	1.197	1.508
	(0.159)	(0.093)	(0.150)	(0.116)	(0.190)
Returns to scale, $\sum_j \beta_{cj}$	1.169	1.165	1.165	1.208	1.156
	(0.052)	(0.052)	(0.055)	(0.055)	(0.077)
λ_{ict}_median	399.41	419.44	375.07	406.41	316.87
	(71.12)	(105.96)	(101.63)	(67.23)	(68.52)
λ_{ict}_IQ	368.10	380.04	346.79	328.08	303.94
	(78.15)	(112.77)	(105.77)	(72.40)	(90.74)
λ_{ict}_90_10	752.22	752.60	698.21	810.79	746.89
	(168.29)	(235.56)	(233.69)	(210.07)	(282.44)
Productivity persistence, ρ_c	0.630	0.601	0.631	0.581	0.623
	(0.060)	(0.061)	(0.061)	(0.072)	(0.096)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	0.070	0.064	0.062	0.033	0.124
	(0.017)	(0.017)	(0.021)	(0.026)	(0.044)
ζ_{ict}_median	0.000	-0.034	0.000	0.000	0.000
	(0.000)	(0.038)	(0.000)	(0.000)	(0.000)
ζ_{ict}_90_10	0.000	0.098	0.096	0.000	0.000
	(0.000)	(0.094)	(0.068)	(0.000)	(0.000)
J-statistic	0.969	0.932	1.093	0.848	0.445
Adjusted R^2	0.807	0.807	0.807	0.807	0.794
$N \times T$	510	510	510	306	198

(1) Original estimates.
(2) ζ_{ict} as a function of observed irrigation equipment as in (A5).
(3) Common ζ_{ict} over time as in (A4).
(4) Restricts estimation sample to 2007–2011.
(5) Restricts estimation sample to 2012–2015.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A11. Sensitivity to Technical Change: Annual Irrigated

	(1)	(2)	(3)	(4)	(5)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.206	0.190	0.146	0.192	0.283
	(0.031)	(0.034)	(0.035)	(0.049)	(0.049)
$\frac{\partial f_c}{\partial w}$_10	0.087	0.082	0.066	0.075	0.159
	(0.021)	(0.022)	(0.025)	(0.028)	(0.052)
$\frac{\partial f_c}{\partial w}$_25	0.151	0.143	0.116	0.134	0.243
	(0.029)	(0.028)	(0.033)	(0.041)	(0.056)
$\frac{\partial f_c}{\partial w}$_75	0.265	0.245	0.186	0.261	0.339
	(0.038)	(0.042)	(0.043)	(0.062)	(0.055)
$\frac{\partial f_c}{\partial w}$_90	0.297	0.270	0.203	0.289	0.374
	(0.042)	(0.046)	(0.046)	(0.069)	(0.061)
Rainwater coefficient, ϑ_c	1.048	1.104	1.094	1.052	1.215
	(0.161)	(0.086)	(0.109)	(0.138)	(0.115)
Returns to scale, $\sum_j \beta_{cj}$	1.131	1.126	1.090	1.323	1.088
	(0.079)	(0.076)	(0.078)	(0.156)	(0.116)
λ_{ict}_median	79.75	72.80	56.34	77.52	100.56
	(14.45)	(15.22)	(15.88)	(34.32)	(18.09)
λ_{ict}_IQ	140.18	127.31	98.56	529.87	61.39
	(103.84)	(106.08)	(99.11)	(178.73)	(18.67)
λ_{ict}_90_10	694.69	654.98	515.51	973.43	209.59
	(183.88)	(192.83)	(186.18)	(253.86)	(102.42)
Productivity persistence, ρ_c	0.432	0.430	0.415	0.543	0.802
	(0.082)	(0.086)	(0.083)	(0.097)	(0.122)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	0.056	0.050	0.005	−0.141	−0.031
	(0.054)	(0.054)	(0.055)	(0.124)	(0.061)
ζ_{ict}_median	0.000	−0.046	−0.087	0.000	0.000
	(0.000)	(0.083)	(0.128)	(0.000)	(0.000)
ζ_{ict}_90_10	0.000	0.324	0.087	0.000	0.000
	(0.000)	(0.174)	(0.091)	(0.000)	(0.000)
J-statistic	1.103	1.078	0.656	1.223	0.487
Adjusted R^2	0.797	0.797	0.797	0.636	NaN
$N \times T$	170	170	170	90	74

(1) Original estimates.

(2) ζ_{ict} as a function of observed irrigation equipment as in (A5).

(3) Common ζ_{ict} over time as in (A4).

(4) Restricts estimation sample to 2007–2011.

(5) Restricts estimation sample to 2012–2015.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A12. Sensitivity to Technical Change: Dairy

	(1)	(2)	(3)	(4)	(5)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.164	0.125	0.273	0.121	0.214
	(0.049)	(0.042)	(0.071)	(0.031)	(0.021)
$\frac{\partial f_c}{\partial w}$_10	0.075	0.039	0.101	0.063	0.112
	(0.029)	(0.026)	(0.035)	(0.020)	(0.017)
$\frac{\partial f_c}{\partial w}$_25	0.104	0.058	0.157	0.090	0.178
	(0.038)	(0.033)	(0.048)	(0.027)	(0.024)
$\frac{\partial f_c}{\partial w}$_75	0.209	0.164	0.362	0.149	0.263
	(0.068)	(0.056)	(0.089)	(0.040)	(0.025)
$\frac{\partial f_c}{\partial w}$_90	0.263	0.243	0.465	0.186	0.284
	(0.079)	(0.074)	(0.108)	(0.046)	(0.027)
Rainwater coefficient, ϑ_c	0.148	1.066	0.049	0.610	1.021
	(0.243)	(0.352)	(0.251)	(0.405)	(0.051)
Returns to scale, $\sum_j \beta_{cj}$	1.039	0.995	1.049	1.014	1.015
	(0.041)	(0.044)	(0.052)	(0.051)	(0.066)
λ_{ict}_median	272.64	174.22	423.74	266.62	273.26
	(89.24)	(75.78)	(115.91)	(75.93)	(33.89)
λ_{ict}_IQ	137.32	77.24	182.96	170.92	149.27
	(58.63)	(51.87)	(68.85)	(63.68)	(34.61)
λ_{ict}_90_10	317.98	206.03	471.59	357.45	330.70
	(125.64)	(109.30)	(145.91)	(136.41)	(66.92)
Productivity persistence, ρ_c	0.324	0.310	0.310	0.319	0.293
	(0.066)	(0.101)	(0.075)	(0.092)	(0.161)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	−0.101	−0.071	−0.068	−0.104	0.006
	(0.022)	(0.026)	(0.049)	(0.044)	(0.026)
ζ_{ict}_median	0.000	0.000	0.040	0.000	0.000
	(0.000)	(0.011)	(0.087)	(0.000)	(0.000)
ζ_{ict}_90_10	0.000	1.873	0.040	0.000	0.000
	(0.000)	(0.485)	(0.056)	(0.000)	(0.000)
J-statistic	1.004	1.039	0.957	1.012	1.163
Adjusted R^2	0.876	0.876	0.876	0.921	NaN
$N \times T$	254	254	254	149	104

(1) Original estimates.
(2) ζ_{ict} as a function of observed irrigation equipment as in (A5).
(3) Common ζ_{ict} over time as in (A4).
(4) Restricts estimation sample to 2007–2011.
(5) Restricts estimation sample to 2012–2015.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A13. Sensitivity to Functional Form: Perennial Irrigated

	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.246	0.300	0.397	0.182	0.175	0.338
	(0.040)	(0.106)	(0.115)	(0.242)	(0.405)	(0.496)
$\frac{\partial f_c}{\partial w}$_10	0.141	0.137	0.239	0.068	0.101	0.189
	(0.028)	(0.099)	(0.069)	(0.227)	(0.396)	(0.420)
$\frac{\partial f_c}{\partial w}$_25	0.207	0.217	0.335	0.116	0.143	0.296
	(0.035)	(0.119)	(0.096)	(0.255)	(0.388)	(0.504)
$\frac{\partial f_c}{\partial w}$_75	0.301	0.392	0.483	0.249	0.211	0.400
	(0.048)	(0.105)	(0.139)	(0.255)	(0.427)	(0.518)
$\frac{\partial f_c}{\partial w}$_90	0.326	0.434	0.511	0.288	0.247	0.441
	(0.052)	(0.093)	(0.147)	(0.255)	(0.446)	(0.505)
Returns to scale, $\sum_j \beta_{cj}$	1.169	0.838	1.442	1.392	1.498	1.538
	(0.052)	(0.107)	(0.046)	(0.079)	(0.062)	(0.021)
λ_{ict}_median	399.41	492.23	652.53	304.93	289.20	544.84
	(71.12)	(172.94)	(186.26)	(392.29)	(647.41)	(805.09)
λ_{ict}_IQ	368.10	463.03	599.07	291.10	259.69	466.20
	(78.15)	(143.81)	(178.01)	(321.63)	(458.09)	(584.25)
λ_{ict}_90_10	752.22	913.22	1200.23	590.06	569.61	982.53
	(168.29)	(358.66)	(382.70)	(861.99)	(1239.66)	(1573.96)
Productivity persistence, ρ_c	0.630	0.654	0.610	0.665	0.580	0.728
	(0.060)	(0.065)	(0.063)	(0.081)	(0.069)	(0.054)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	0.070	0.069	0.059	0.066	0.063	0.067
	(0.017)	(0.017)	(0.016)	(0.017)	(0.017)	(0.016)
J-statistic	0.969	0.564	0.479	0.927	1.097	2.614
Adjusted R^2	0.807	0.807	0.807	0.807	0.807	0.807
$N \times T$	510	510	510	510	510	510

(1) Nested CES: original estimates of (2) in Table 3.

(2) Leontief ($\sigma_c \to 0$) without overwatering.

(3) Cobb-Douglas ($\sigma_c = 1$) with separable rain: $f_c = \theta_{cW} w_{ict} + \theta_{cK} k_{ict} + \sum_j \beta_{cj} x^j_{ict}$.

(4) Cobb-Douglas ($\sigma_c = 1$) with rain as a perfect substitute: $f_c = \theta_{cW} \ln(W_{ict} + \vartheta_c R_{ict}) + \theta_{cK} k_{ict} + \sum_j \beta_{cj} x^j_{ict}$.

(5) Translog: $f_c = \sum_{\ell+m+n\leq 2} \theta_{c,\ell mn} w^{\ell}_{ict} \ln(E^R_{ict} - E^V_{ict})^m \ln k^n_{ict}$.

(6) Quadratic: $F_c = \sum_{\ell+m+n\leq 2} \theta_{c,\ell mn} W^{\ell}_{ict} (E^R_{ict} - E^V_{ict})^m K^n_{ict}$.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A14. Sensitivity to Functional Form: Annual Irrigated

	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.206	0.327	0.283	0.127	0.448	0.818
	(0.031)	(0.130)	(0.141)	(0.231)	(0.582)	(0.322)
$\frac{\partial f_c}{\partial w}$_10	0.087	0.149	0.132	0.031	0.355	0.528
	(0.021)	(0.166)	(0.064)	(0.182)	(0.491)	(0.422)
$\frac{\partial f_c}{\partial w}$_25	0.151	0.261	0.229	0.070	0.409	0.758
	(0.029)	(0.145)	(0.108)	(0.225)	(0.545)	(0.453)
$\frac{\partial f_c}{\partial w}$_75	0.265	0.415	0.357	0.174	0.499	0.944
	(0.038)	(0.153)	(0.178)	(0.252)	(0.602)	(0.231)
$\frac{\partial f_c}{\partial w}$_90	0.297	0.458	0.392	0.230	0.530	0.970
	(0.042)	(0.186)	(0.196)	(0.260)	(0.662)	(0.156)
Returns to scale, $\sum_j \beta_{cj}$	1.131	0.932	1.483	1.412	1.657	1.605
	(0.079)	(0.135)	(0.109)	(0.122)	(0.167)	(0.033)
λ_{ict}_median	79.75	126.08	109.25	45.98	213.12	395.59
	(14.45)	(61.56)	(54.00)	(92.90)	(256.02)	(143.49)
λ_{ict}_IQ	140.18	220.18	188.46	94.91	481.19	725.54
	(103.84)	(238.22)	(128.76)	(210.76)	(700.10)	(534.80)
λ_{ict}_90_10	694.69	1151.72	988.19	425.88	1401.16	2473.63
	(183.88)	(619.43)	(516.71)	(816.98)	(1859.76)	(1530.97)
Productivity persistence, ρ_c	0.432	0.430	0.398	0.442	0.372	0.552
	(0.082)	(0.126)	(0.084)	(0.083)	(0.136)	(0.082)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	0.056	0.038	0.071	0.057	0.083	0.094
	(0.054)	(0.060)	(0.053)	(0.054)	(0.068)	(0.072)
J-statistic	1.103	26863.885	0.869	1.604	1.097	1.985
Adjusted R^2	0.797	0.797	0.797	0.797	0.797	0.797
$N \times T$	170	170	170	170	170	170

(1) Nested CES: original estimates of (2) in Table 3.

(2) Leontief ($\sigma_c \to 0$) without overwatering.

(3) Cobb-Douglas ($\sigma_c = 1$) with separable rain: $f_c = \theta_{cW} w_{ict} + \theta_{cK} k_{ict} + \sum_j \beta_{cj} x^j_{ict}$.

(4) Cobb-Douglas ($\sigma_c = 1$) with rain as a perfect substitute: $f_c = \theta_{cW} \ln(W_{ict} + \vartheta_c R_{ict}) + \theta_{cK} k_{ict} + \sum_j \beta_{cj} x^j_{ict}$.

(5) Translog: $f_c = \sum_{\ell+m+n\leq 2} \theta_{c,\ell mn} w^\ell_{ict} \ln(E^R_{ict} - E^V_{ict})^m \ln k^n_{ict}$.

(6) Quadratic: $F_c = \sum_{\ell+m+n\leq 2} \theta_{c,\ell mn} W^\ell_{ict} (E^R_{ict} - E^V_{ict})^m K^n_{ict}$.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A15. Sensitivity to Functional Form: Dairy

	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.164	0.014	0.027	0.034	0.084	0.269
	(0.049)	(0.018)	(0.017)	(0.001)	(0.138)	(0.192)
$\frac{\partial f_c}{\partial w}$_10	0.075	0.007	0.014	0.020	0.048	0.061
	(0.029)	(0.010)	(0.009)	(0.000)	(0.137)	(0.086)
$\frac{\partial f_c}{\partial w}$_25	0.104	0.010	0.019	0.027	0.061	0.117
	(0.038)	(0.013)	(0.012)	(0.001)	(0.135)	(0.119)
$\frac{\partial f_c}{\partial w}$_75	0.209	0.018	0.034	0.042	0.104	0.388
	(0.068)	(0.024)	(0.021)	(0.002)	(0.141)	(0.227)
$\frac{\partial f_c}{\partial w}$_90	0.263	0.021	0.039	0.046	0.124	0.563
	(0.079)	(0.027)	(0.024)	(0.002)	(0.147)	(0.258)
Returns to scale, $\sum_j \beta_{cj}$	1.039	0.271	1.431	1.435	1.184	1.260
	(0.041)	(0.017)	(0.082)	(0.077)	(0.065)	(0.013)
λ_{ict}_median	272.64	24.35	45.12	58.09	140.83	405.82
	(89.24)	(31.98)	(28.08)	(1.76)	(253.61)	(294.39)
λ_{ict}_IQ	137.32	19.32	35.80	47.38	199.06	280.91
	(58.63)	(27.20)	(24.61)	(1.89)	(197.66)	(220.36)
λ_{ict}_90_10	317.98	45.36	84.06	106.92	405.52	560.31
	(125.64)	(59.24)	(52.42)	(3.80)	(397.86)	(470.84)
Productivity persistence, ρ_c	0.324	0.931	0.387	0.388	0.920	0.565
	(0.066)	(0.021)	(0.130)	(0.122)	(0.051)	(0.098)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	−0.101	0.008	−0.103	−0.103	0.008	−0.140
	(0.022)	(0.014)	(0.039)	(0.036)	(0.023)	(0.037)
J-statistic	1.004	1.718	1.059	1.061	1.353	1.866
Adjusted R^2	0.876	0.876	0.876	0.876	0.876	0.876
$N \times T$	254	254	254	254	254	254

(1) Nested CES: original estimates of (2) in Table 3.

(2) Leontief ($\sigma_c \to 0$) without overwatering.

(3) Cobb-Douglas ($\sigma_c = 1$) with separable rain: $f_c = \theta_{cW} w_{ict} + \theta_{cK} k_{ict} + \sum_j \beta_{cj} x^j_{ict}$.

(4) Cobb-Douglas ($\sigma_c = 1$) with rain as a perfect substitute: $f_c = \theta_{cW} \ln(W_{ict} + \vartheta_c R_{ict}) + \theta_{cK} k_{ict} + \sum_j \beta_{cj} x^j_{ict}$.

(5) Translog: $f_c = \sum_{\ell+m+n \leq 2} \theta_{c,\ell mn} w^{\ell}_{ict} \ln(E^R_{ict} - E^V_{ict})^m \ln k^n_{ict}$.

(6) Quadratic: $F_c = \sum_{\ell+m+n \leq 2} \theta_{c,\ell mn} W^{\ell}_{ict} (E^R_{ict} - E^V_{ict})^m K^n_{ict}$.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A16. Sensitivity to Rainfall Specification: Perennial Irrigated

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.246	0.393	0.352	0.218	0.300	0.261	0.260	0.245
	(0.040)	(0.029)	(0.036)	(0.047)	(0.037)	(0.158)	(0.040)	(0.081)
$\frac{\partial f_c}{\partial w}$_10	0.141	0.347	0.309	0.156	0.209	0.153	0.152	0.148
	(0.028)	(0.032)	(0.038)	(0.034)	(0.029)	(0.092)	(0.028)	(0.047)
$\frac{\partial f_c}{\partial w}$_25	0.207	0.385	0.344	0.201	0.275	0.222	0.220	0.212
	(0.035)	(0.029)	(0.037)	(0.042)	(0.035)	(0.135)	(0.035)	(0.067)
$\frac{\partial f_c}{\partial w}$_75	0.301	0.415	0.373	0.252	0.348	0.318	0.316	0.295
	(0.048)	(0.029)	(0.036)	(0.054)	(0.044)	(0.193)	(0.050)	(0.099)
$\frac{\partial f_c}{\partial w}$_90	0.326	0.425	0.383	0.263	0.365	0.342	0.341	0.316
	(0.052)	(0.029)	(0.037)	(0.058)	(0.045)	(0.206)	(0.053)	(0.110)
Rainwater coefficient, ϑ_c	1.081	0.000	0.000	0.500	0.500	1.000	1.000	0.866
	(0.159)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.204)
Returns to scale, $\sum_j \beta_{cj}$	1.169	1.154	1.157	1.171	1.174	1.173	1.160	1.145
	(0.052)	(0.047)	(0.045)	(0.050)	(0.048)	(0.052)	(0.050)	(0.050)
λ_{ict}_median	399.41	648.22	581.52	358.58	493.63	423.72	421.43	397.20
	(71.12)	(57.11)	(71.14)	(79.36)	(62.64)	(259.14)	(68.54)	(129.85)
λ_{ict}_IQ	368.10	559.85	498.23	325.82	448.62	398.69	396.52	365.79
	(78.15)	(111.21)	(105.93)	(96.63)	(79.47)	(231.63)	(78.25)	(125.66)
λ_{ict}_90_10	752.22	1357.01	1208.25	649.55	894.62	799.23	794.95	732.88
	(168.29)	(212.14)	(220.41)	(190.94)	(166.69)	(538.08)	(161.91)	(265.91)
Productivity persistence, ρ_c	0.630	0.576	0.571	0.616	0.607	0.624	0.627	0.631
	(0.060)	(0.061)	(0.068)	(0.055)	(0.060)	(0.054)	(0.061)	(0.052)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	0.070	0.063	0.061	0.069	0.066	0.071	0.069	0.069
	(0.017)	(0.015)	(0.016)	(0.015)	(0.016)	(0.016)	(0.017)	(0.016)
J-statistic	0.969	0.972	0.848	0.848	0.901	1.043	0.980	0.985
Adjusted R^2	0.807	0.807	0.807	0.807	0.807	0.807	0.807	0.807
$N \times T$	510	510	510	510	510	510	510	510

Odd columns control for summer and winter rainfall separately rather than total annual rainfall.
(1) Original estimates.
(2), (3) Imposes $\vartheta_c = 0$.
(4), (5) Imposes $\vartheta_c = \frac{1}{2}$.
(6), (7) Imposes $\vartheta_c = 1$.
(8) Estimates $\hat{\vartheta}_c$.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A17. Sensitivity to Rainfall Specification: Annual Irrigated

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.206	0.332	0.313	0.286	0.256	0.245	0.226	0.210
	(0.031)	(0.048)	(0.042)	(0.041)	(0.029)	(0.035)	(0.027)	(0.034)
$\frac{\partial f_c}{\partial w}$_10	0.087	0.261	0.259	0.147	0.137	0.104	0.097	0.082
	(0.021)	(0.049)	(0.044)	(0.029)	(0.025)	(0.022)	(0.019)	(0.025)
$\frac{\partial f_c}{\partial w}$_25	0.151	0.305	0.291	0.233	0.210	0.179	0.166	0.147
	(0.029)	(0.045)	(0.042)	(0.037)	(0.029)	(0.032)	(0.024)	(0.035)
$\frac{\partial f_c}{\partial w}$_75	0.265	0.370	0.342	0.352	0.311	0.314	0.290	0.273
	(0.038)	(0.049)	(0.042)	(0.047)	(0.036)	(0.043)	(0.032)	(0.042)
$\frac{\partial f_c}{\partial w}$_90	0.297	0.385	0.355	0.385	0.339	0.354	0.325	0.315
	(0.042)	(0.050)	(0.043)	(0.050)	(0.037)	(0.048)	(0.037)	(0.045)
Rainwater coefficient, ϑ_c	1.048	0.000	0.000	0.500	0.500	1.000	1.000	1.303
	(0.161)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.365)
Returns to scale, $\sum_j \beta_{cj}$	1.131	1.109	1.110	1.093	1.156	1.177	1.141	1.122
	(0.079)	(0.086)	(0.086)	(0.085)	(0.078)	(0.087)	(0.076)	(0.085)
λ_{ict}_median	79.75	149.06	141.65	114.37	105.16	94.43	86.86	83.43
	(14.45)	(25.39)	(24.57)	(19.81)	(15.85)	(16.96)	(13.70)	(16.62)
λ_{ict}_IQ	140.18	309.64	297.09	184.80	176.91	166.66	153.55	142.51
	(103.84)	(142.24)	(131.04)	(144.14)	(132.27)	(123.51)	(115.17)	(104.98)
λ_{ict}_90_10	694.69	1059.58	997.25	1021.39	899.35	817.36	757.50	719.86
	(183.88)	(367.26)	(349.50)	(267.04)	(250.47)	(201.56)	(186.35)	(209.28)
Productivity persistence, ρ_c	0.432	0.395	0.391	0.430	0.428	0.451	0.435	0.441
	(0.082)	(0.087)	(0.080)	(0.084)	(0.082)	(0.085)	(0.083)	(0.083)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	0.056	0.056	0.056	0.138	0.062	0.047	0.049	0.052
	(0.054)	(0.058)	(0.055)	(0.063)	(0.054)	(0.070)	(0.054)	(0.069)
J-statistic	1.103	0.958	1.078	0.465	1.093	1.057	1.155	1.001
Adjusted R^2	0.797	0.797	0.797	0.797	0.797	0.797	0.797	0.797
$N \times T$	170	170	170	170	170	170	170	170

See Table A16 for list of specifications.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A18. Sensitivity to Rainfall Specification: Dairy

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\mathbb{E}[\frac{\partial f_c}{\partial w}]$	0.164	0.339	0.287	0.061	0.222	0.042	0.179	0.056
	(0.049)	(0.033)	(0.043)	(0.099)	(0.069)	(0.078)	(0.076)	(0.046)
$\frac{\partial f_c}{\partial w}$_10	0.075	0.296	0.226	0.021	0.138	0.022	0.094	0.037
	(0.029)	(0.042)	(0.051)	(0.070)	(0.052)	(0.045)	(0.043)	(0.025)
$\frac{\partial f_c}{\partial w}$_25	0.104	0.315	0.252	0.031	0.177	0.030	0.125	0.046
	(0.038)	(0.038)	(0.049)	(0.087)	(0.064)	(0.059)	(0.058)	(0.036)
$\frac{\partial f_c}{\partial w}$_75	0.209	0.362	0.319	0.078	0.277	0.055	0.232	0.068
	(0.068)	(0.030)	(0.039)	(0.122)	(0.085)	(0.102)	(0.099)	(0.061)
$\frac{\partial f_c}{\partial w}$_90	0.263	0.379	0.346	0.108	0.312	0.062	0.268	0.075
	(0.079)	(0.026)	(0.037)	(0.127)	(0.086)	(0.113)	(0.108)	(0.069)
Rainwater coefficient, ϑ_c	0.148	0.000	0.000	0.500	0.500	1.000	1.000	0.396
	(0.243)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.199)
Returns to scale, $\sum_j \beta_{cj}$	1.039	1.037	1.054	1.009	1.044	0.987	1.008	0.997
	(0.041)	(0.041)	(0.048)	(0.042)	(0.042)	(0.044)	(0.044)	(0.041)
λ_{ict}_median	272.64	618.63	529.51	89.64	374.54	73.32	311.93	95.34
	(89.24)	(80.56)	(93.03)	(177.86)	(122.67)	(136.76)	(133.47)	(82.52)
λ_{ict}_IQ	137.32	590.46	446.99	40.96	275.07	49.68	198.36	76.17
	(58.63)	(109.02)	(128.38)	(143.73)	(106.99)	(96.89)	(77.75)	(50.17)
λ_{ict}_90_10	317.98	1082.54	866.10	98.51	600.49	123.99	510.81	164.44
	(125.64)	(177.87)	(222.13)	(292.87)	(221.07)	(213.18)	(180.57)	(118.63)
Productivity persistence, ρ_c	0.324	0.377	0.329	0.343	0.303	0.363	0.296	0.373
	(0.066)	(0.062)	(0.067)	(0.068)	(0.070)	(0.079)	(0.078)	(0.068)
$\mathbb{E}[\omega_{ict} - \omega_{ic,t-1}]$	−0.101	−0.102	−0.095	−0.106	−0.100	−0.115	−0.098	−0.112
	(0.022)	(0.023)	(0.025)	(0.022)	(0.023)	(0.021)	(0.024)	(0.021)
J-statistic	1.004	1.421	1.089	1.025	2.207	1.039	2.882	1.051
Adjusted R^2	0.876	0.876	0.876	0.876	0.876	0.876	0.876	0.876
$N \times T$	254	254	254	254	254	254	254	254

See Table A16 for list of specifications.

Standard errors block-bootstrapped at the farm level (1000 iterations) in parentheses..

Table A19. Misallocation and Water Trading

	Interquartile shadow value range		
	Pre-trade	Post-trade	Difference
All	653.42	631.21	−22.21
	(135.42)	(133.61)	(24.78)
Years			
2007	737.87	716.66	−21.21
	(183.91)	(180.28)	(35.01)
2008	763.53	713.46	−50.07
	(233.39)	(243.69)	(80.34)
2009	967.57	881.57	−86.00
	(288.58)	(311.24)	(94.47)
2010	616.79	563.50	−53.28
	(277.15)	(242.59)	(80.79)
2011	342.56	312.99	−29.57
	(141.59)	(114.94)	(55.93)
2012	262.56	251.61	−10.96
	(91.73)	(91.51)	(41.86)
2013	237.20	220.45	−16.75
	(124.91)	(115.24)	(43.91)
2014	400.41	375.56	−24.85
	(139.62)	(139.20)	(31.91)
2015	613.61	609.20	−4.40
	(219.72)	(202.14)	(40.36)

	Interdecile shadow value range		
	Pre-trade	Post-trade	Difference
All	1600.40	1566.56	−33.84
	(322.13)	(348.85)	(60.11)
Years			
2007	1545.49	1539.27	−6.22
	(398.16)	(390.14)	(70.81)
2008	1888.62	1777.74	−110.87
	(495.47)	(554.59)	(152.80)
2009	2060.65	2000.31	−60.34
	(599.17)	(777.30)	(287.99)
2010	1891.09	1844.60	−46.49
	(812.64)	(724.12)	(157.60)
2011	755.93	745.86	−10.07
	(433.77)	(364.22)	(93.69)
2012	578.53	531.80	−46.73
	(185.74)	(177.27)	(51.27)
2013	813.80	781.32	−32.48
	(287.44)	(284.76)	(64.18)
2014	921.33	901.66	−19.67
	(362.21)	(352.11)	(44.98)
2015	1292.97	1291.09	−1.89
	(703.47)	(665.06)	(76.08)

Restricted to water-trading farms only. Interquartile range of estimated shadow values evaluated at pre-trade endowments, post-trade observed inputs, and the difference between the two. Standard errors block-bootstrapped at the farm level (5000 iterations) in parentheses.

Table A20. Realized Gains from Trade – Additional Results

	Gains from trade			Reallocation	
	%	%, traders	AUD/ML	realloc (%)	traders (%)
All	0.051	0.091	338.52	0.133	0.51
	[0.016, 0.071]	[0.037, 0.127]	[−21.23, 467.53]	[0.117, 0.148]	[0.48, 0.53]
Years					
2007	0.026	0.058	154.50	0.105	0.48
	[−0.045, 0.053]	[−0.067, 0.123]	[−489.13, 327.69]	[0.080, 0.129]	[0.44, 0.52]
2008	0.084	0.125	462.74	0.221	0.71
	[0.040, 0.254]	[0.063, 0.378]	[126.11, 1434.66]	[0.157, 0.275]	[0.66, 0.76]
2009	0.129	0.156	807.12	0.261	0.66
	[0.000, 0.188]	[0.010, 0.226]	[−816.18, 1131.74]	[0.208, 0.314]	[0.61, 0.71]
2010	0.089	0.121	840.61	0.153	0.48
	[0.025, 0.146]	[0.054, 0.194]	[−567.27, 1403.01]	[0.108, 0.195]	[0.42, 0.54]
2011	0.009	0.055	181.80	0.052	0.19
	[−0.001, 0.016]	[0.019, 0.102]	[6.04, 339.85]	[0.023, 0.075]	[0.14, 0.24]
2012	0.015	0.037	116.79	0.072	0.28
	[−0.014, 0.027]	[−0.031, 0.067]	[−118.88, 215.79]	[0.048, 0.094]	[0.23, 0.33]
2013	0.034	0.053	141.68	0.221	0.56
	[−0.015, 0.081]	[−0.020, 0.126]	[−20.62, 346.66]	[0.152, 0.288]	[0.47, 0.64]
2014	0.071	0.094	357.07	0.136	0.66
	[0.017, 0.110]	[0.031, 0.145]	[−7.74, 568.62]	[0.104, 0.165]	[0.60, 0.73]
2015	0.028	0.052	150.41	0.165	0.55
	[0.001, 0.056]	[0.004, 0.102]	[−14.82, 297.65]	[0.125, 0.204]	[0.49, 0.61]
B. Regions					
VIC.Goulburn	0.072	0.119	587.71	0.224	0.46
	[0.022, 0.108]	[0.031, 0.167]	[−159.08, 853.77]	[0.184, 0.262]	[0.41, 0.51]
NSW.Murrumbidgee	0.018	0.030	105.16	0.078	0.52
	[−0.075, 0.063]	[−0.101, 0.102]	[−699.16, 356.45]	[0.059, 0.096]	[0.47, 0.56]
SA.Murray	0.100	0.171	643.38	0.211	0.56
	[0.036, 0.244]	[0.100, 0.411]	[220.92, 1559.38]	[0.139, 0.282]	[0.51, 0.60]
VIC.Murray	0.040	0.088	480.28	0.131	0.43
	[0.003, 0.076]	[0.020, 0.165]	[−146.88, 907.81]	[0.096, 0.161]	[0.38, 0.48]
NSW.Murray	0.041	0.076	185.47	0.166	0.55
	[0.001, 0.061]	[0.019, 0.114]	[−30.03, 271.00]	[0.131, 0.199]	[0.50, 0.61]
C. Crop types					
Perennial irrigated	0.055	0.093	570.06	0.150	0.54
	[0.021, 0.120]	[0.042, 0.201]	[68.22, 1243.81]	[0.111, 0.182]	[0.51, 0.57]
Annual irrigated	0.075	0.129	348.60	0.101	0.48
	[−0.003, 0.097]	[0.023, 0.165]	[−401.22, 486.97]	[0.082, 0.120]	[0.44, 0.52]
Dairy	0.022	0.044	141.81	0.205	0.46
	[−0.007, 0.048]	[−0.013, 0.095]	[−45.90, 307.98]	[0.172, 0.237]	[0.41, 0.51]

Supplement to Table 6. Estimated gains from all water trading for all farms 2007–2015 and then subsets specified by row. Gains from trade defined as discounted sum of (16) over t, reported as the fraction of total irrigated profits (column 1), total irrigated profits of only water-trading farms (column 2), and total trade volume (column 3). Columns 4 and 5 show trade volumes divided by total irrigation volumes and the proportion of farm-years with nonzero trade balances.

Reverse percentile bootstrap confidence intervals reported at the 90% level and constructed from 5000 draws block-bootstrapped at the farm level.

Table A21. Climate Change and Water Variability

A. Climate Predictions for 2030

region	water relative to baseline	regional diff, pp.	regional diff, %
a. median year			
all MDB	−11%	0	0%
Murrumbidgee	−8%	3	−27.3%
Murray	−10%	1	−9.1%
Goulburn	−13%	−2	18.2%
b. wet year			
all MDB	5%	0	0%
Murrumbidgee	10%	5	100%
Murray	2%	−3	−60%
Goulburn	−2%	−7	−140%
c. dry year			
all MDB	−28%	0	0%
Murrumbidgee	−23%	5	−17.9%
Murray	−30%	−2	7.1%
Goulburn	−32%	−4	14.3%

B. Within-Sample Water Variability and Gains from Trade, 2007–2015

	$N \times T$	water scarcity	regional diff, %	GFT	realloc
a. regional allocation					
all	2,059	0.606	0%	5.1%	13.3%
below median	1,223	0.405	−33.2%	7.9%	16.3%
above median	1,016	0.850	40.4%	3.5%	12.2%
b. rainfall (pooled)					
all	2,059	406.0 mm	0%		
below median	1,119	241.4 mm	−40.5%	7.0%	14.9%
above median	1,120	558.3 mm	37.5%	4.0%	12.0%
c. rainfall (within-year)					
all	2,059	406.0 mm	0%		
below median	1,117	319.3 mm	−21.4%	6.3%	13.0%
above median	1,122	480.2 mm	18.3%	4.1%	13.8%
d. rainfall (within-farm)					
all	1,610	424.9 mm	0%		
below median	725	305.2 mm	−28.2%	8.5%	16.7%
above median	885	517.0 mm	21.7%	3.1%	10.4%

A. Predicted declines in regional water resources relative to long-run averages. Columns two and three show regional differences from the basin-wide estimate in percentage points (i.e., $\Delta_r - \Delta_{\text{MDB}}$) and as a percentage of the basinwide estimate (i.e., $\Delta_r - \Delta_{\text{MDB}})/\Delta_{\text{MDB}}$).

Source: Murray-Darling Basin Authority (2010), *Water Availability in the Murray-Darling Basin: An updated assessment.* MDBA Publication, No. 112/10, p. 10.

B. Water endowments for the entire sample and stratified subsets for the four measures of relative water scarcity considered in Table 6. Column three shows regional differences in water availability from the basin-wide average as a percentage of the basin-wide estimate (%Δ).

B Supplementary Figures (Not For Publication)

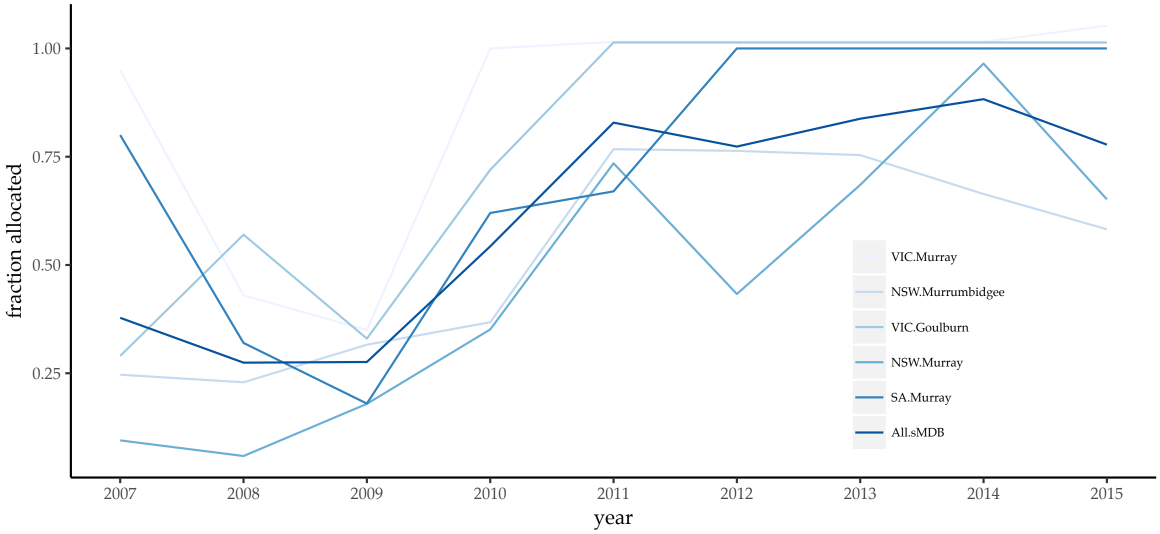


Figure A1. Regional Water-Sharing Rules

Regional water allocations by year as percentages of entitlement volume on issue in 2007. Tabulated in Table A3.

Source: NSW, VIC, and South Australia state government regulatory records.

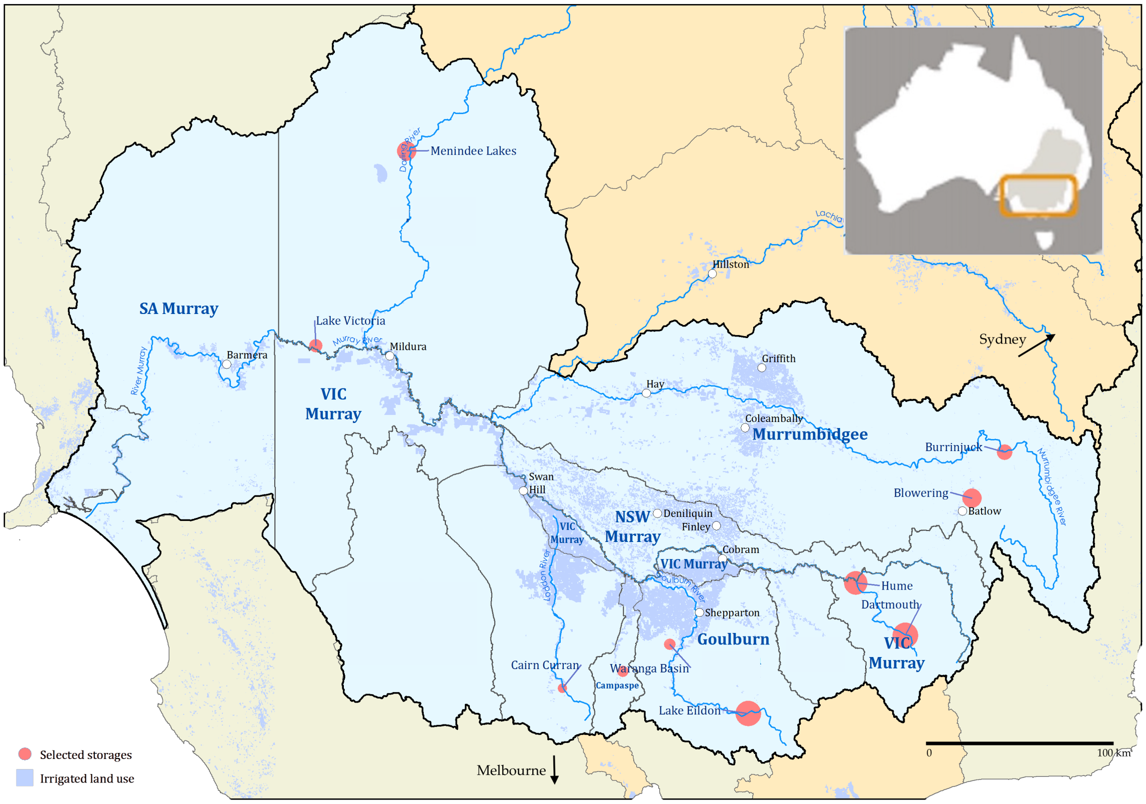


Figure A2. Map of the southern Murray-Darling Basin (sMDB)

River network, regions, irrigation areas, and dams in the southern Murray-Darling Basin.

Source: Australian Department of Agriculture (Hughes *et al.*, 2016a, p. 34, Map 3).

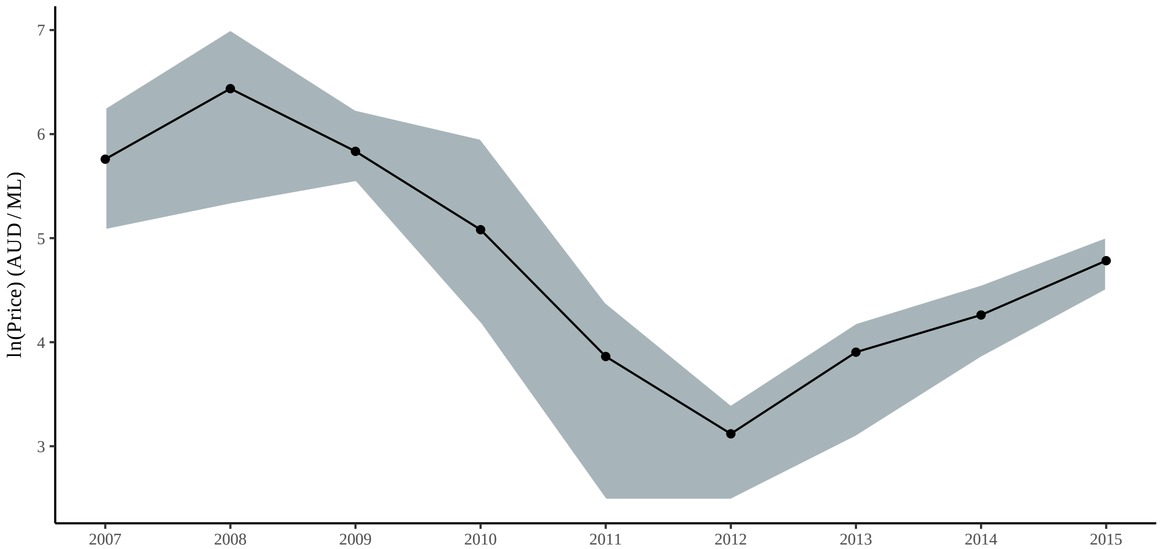


Figure A3. Regional Water Prices

Average annual sMDB-wide water allocation prices, ln(AUD/ML). Blue bands show [5-%,95%] intervals of the water price distribution over all allocation trades within each year (2008–2015) and minimum and maximum annual regional average prices for 2007. Figure A4 and Table A4 contain additional details on within-year water price variation.

Source: MDBA administrative transaction-level allocation water trade data (2008–2015); state registries and a private water broker (2007).

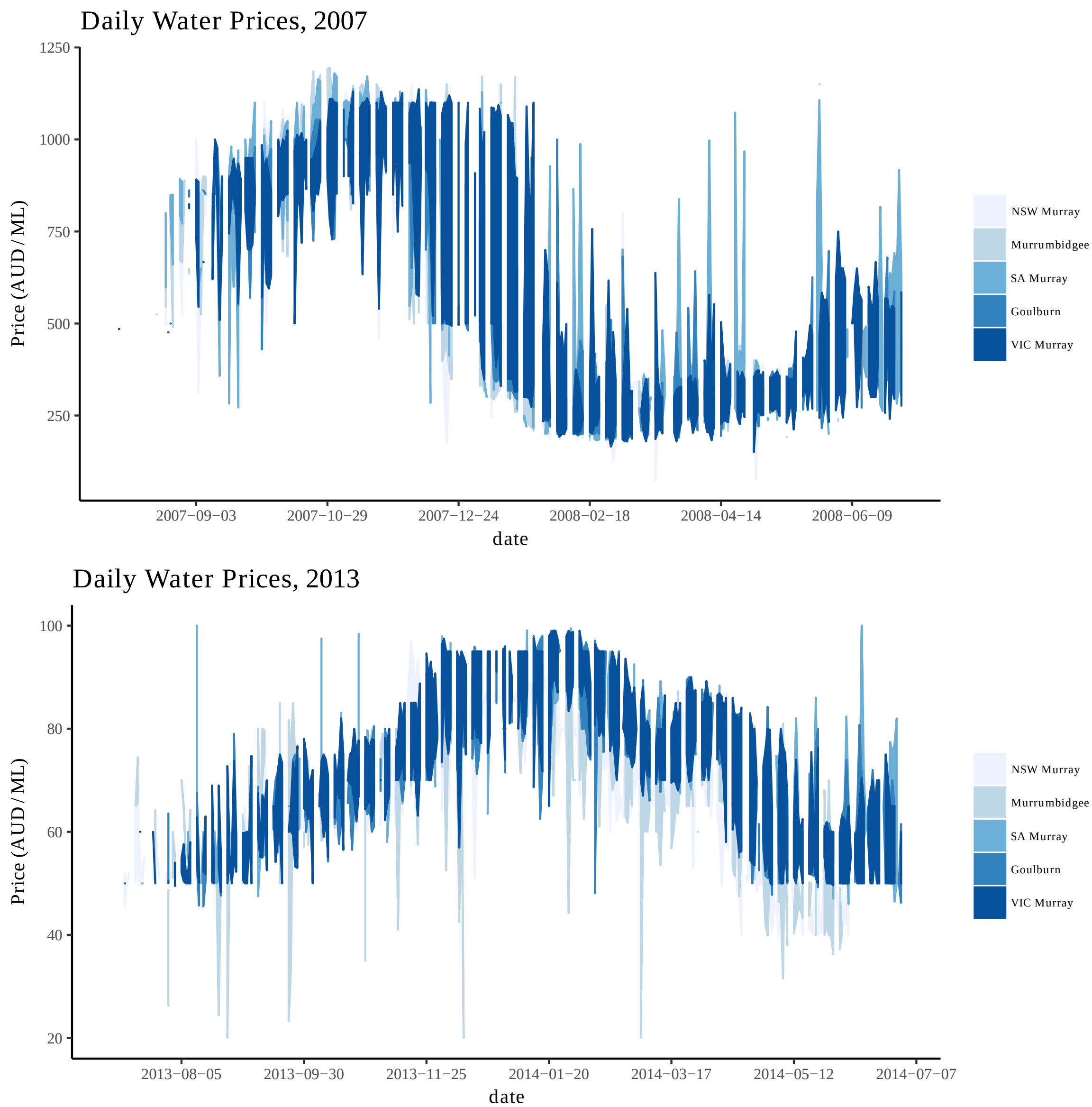


Figure A4. Examples of Intra-Annual Water Price Dispersion

[5%,95%]-tile intervals of daily water prices (AUD/ML) for each region. Note that the scale of the y-axes differ between figures.

Source: MDBA administrative transaction-level water price data.

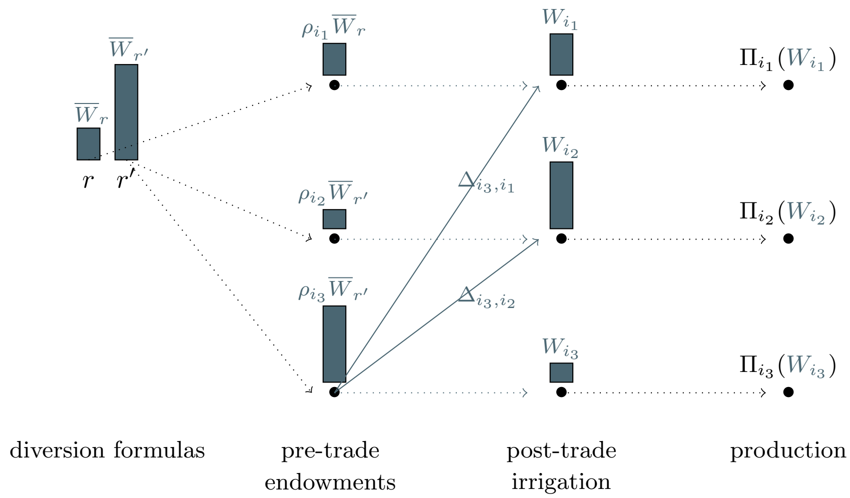


FIGURE A5. EXAMPLE OF WATER ALLOCATIONS AND TRADE

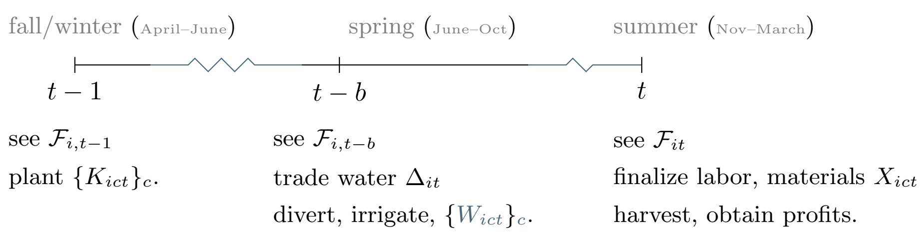


FIGURE A6. AGRICULTURAL CALENDAR

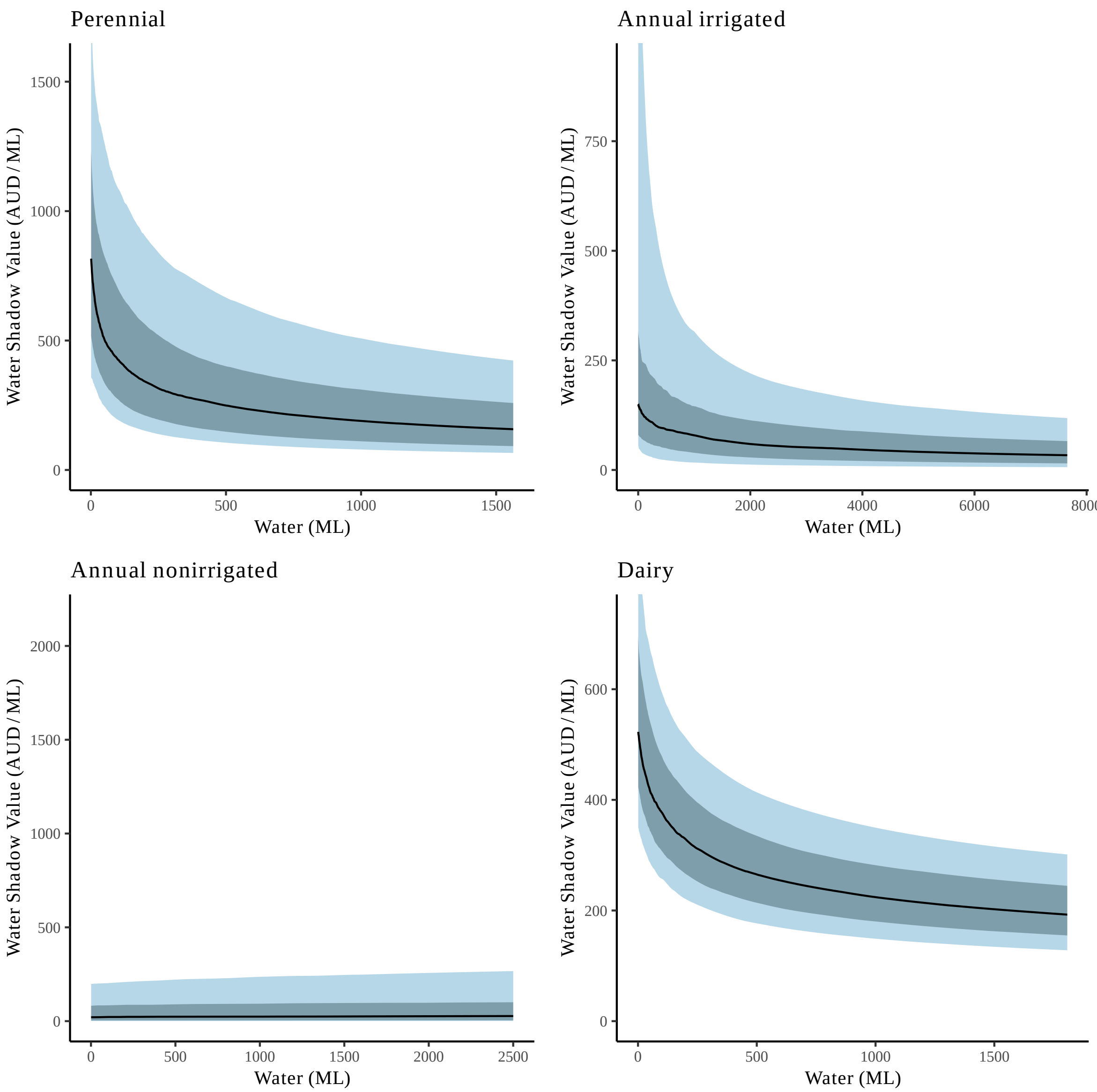


Figure A7. Curvature of Shadow Value Functions

Plots of the estimated shadow value functions given by (14) with interdecile range (light blue band), interquartile range (dark blue), and median values (black line) across farm-years. Note that x-axes differ across figures as they are bounded by the 97.5%-ile volume of irrigation for each irrigated c.

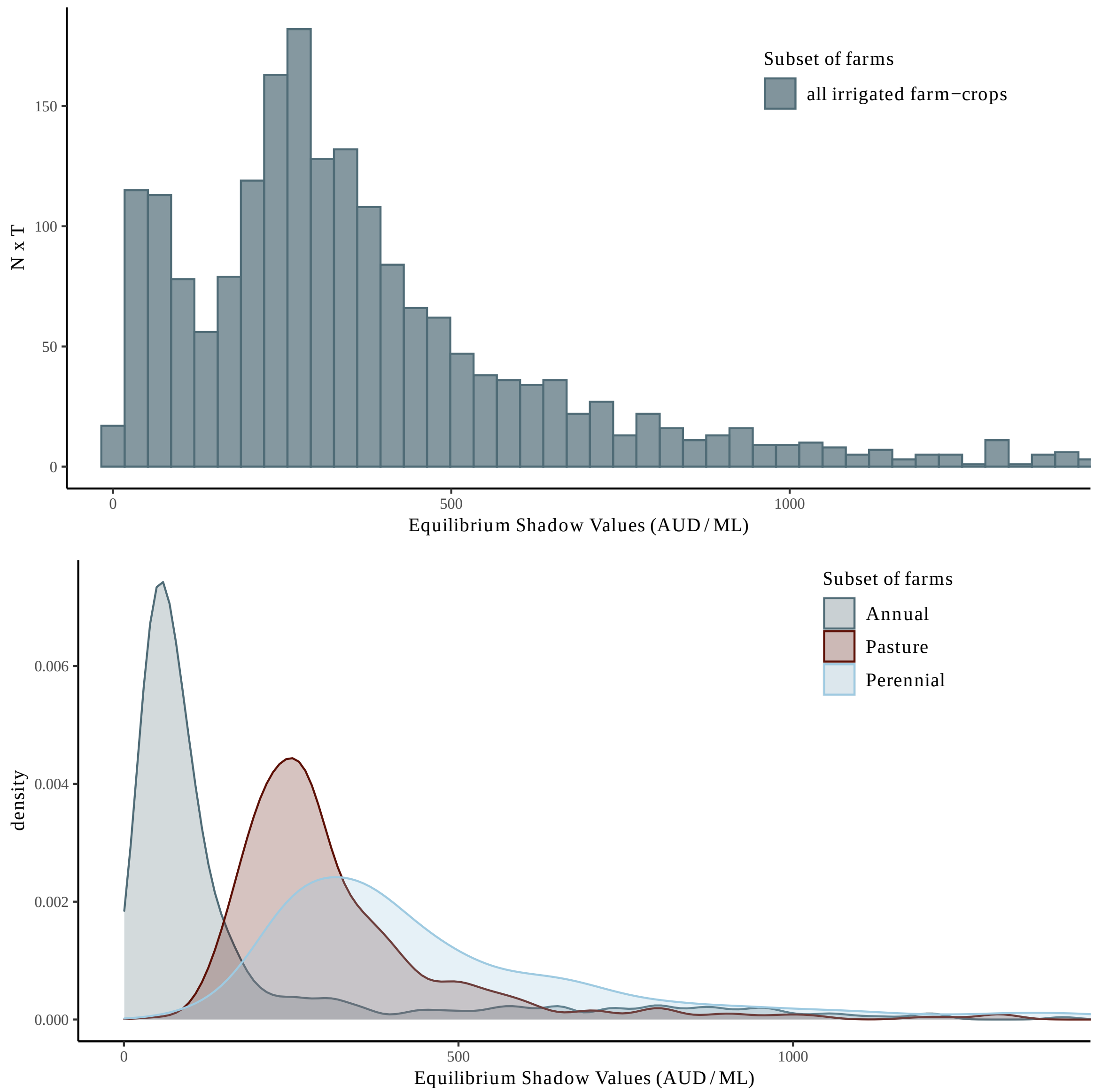


FIGURE A8. WATER SHADOW VALUES AT OBSERVED INPUTS

Pooled histogram (top) and conditional densities (bottom) of estimated farm-crop-level shadow water values obtained from evaluating (14) at observed inputs. The x-axis range is 0 to the 97.5%-tile observation. Nonparametric densities obtained using a Gaussian kernel estimator with a Silverman (1986) optimal bandwidth.

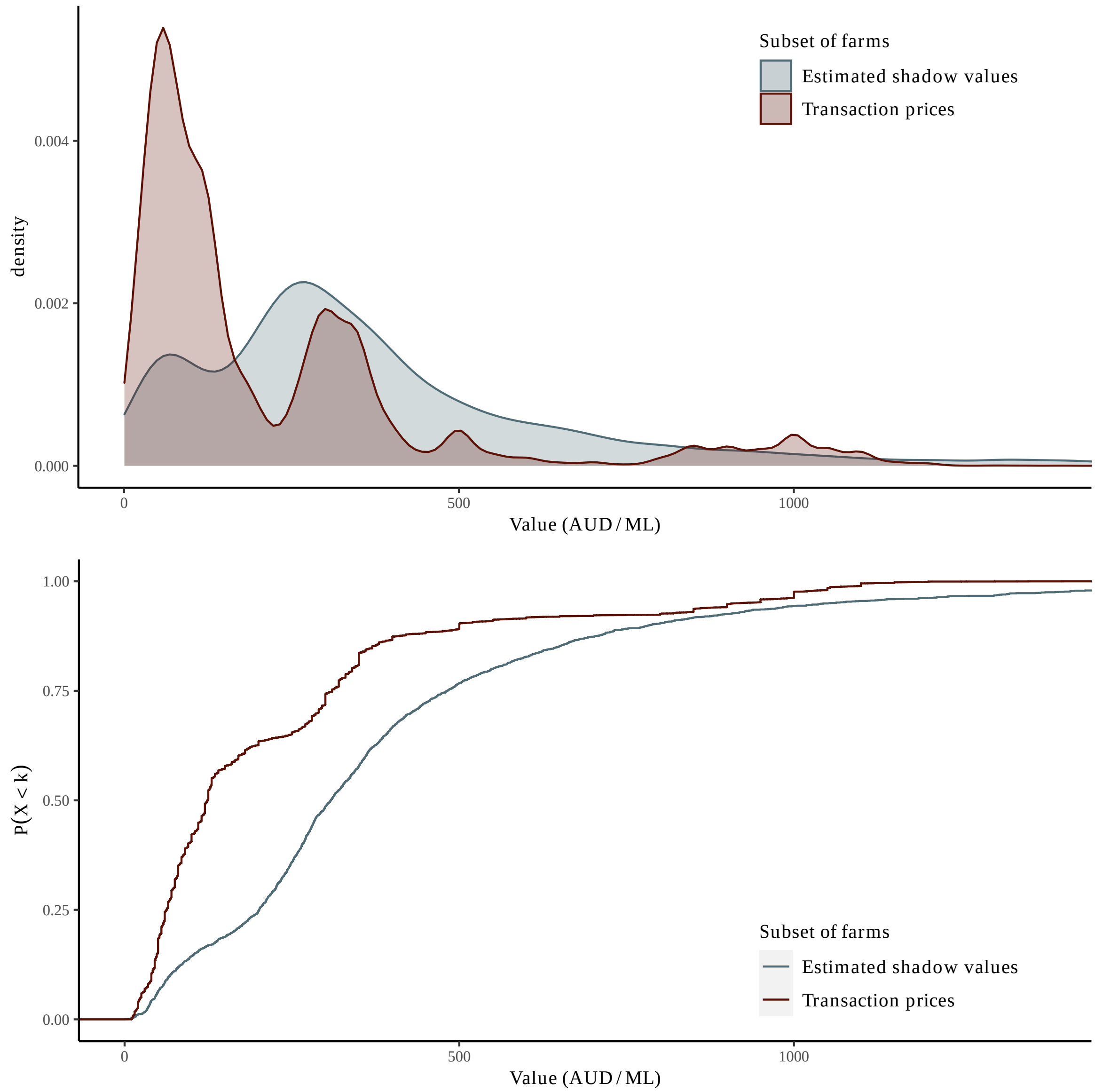
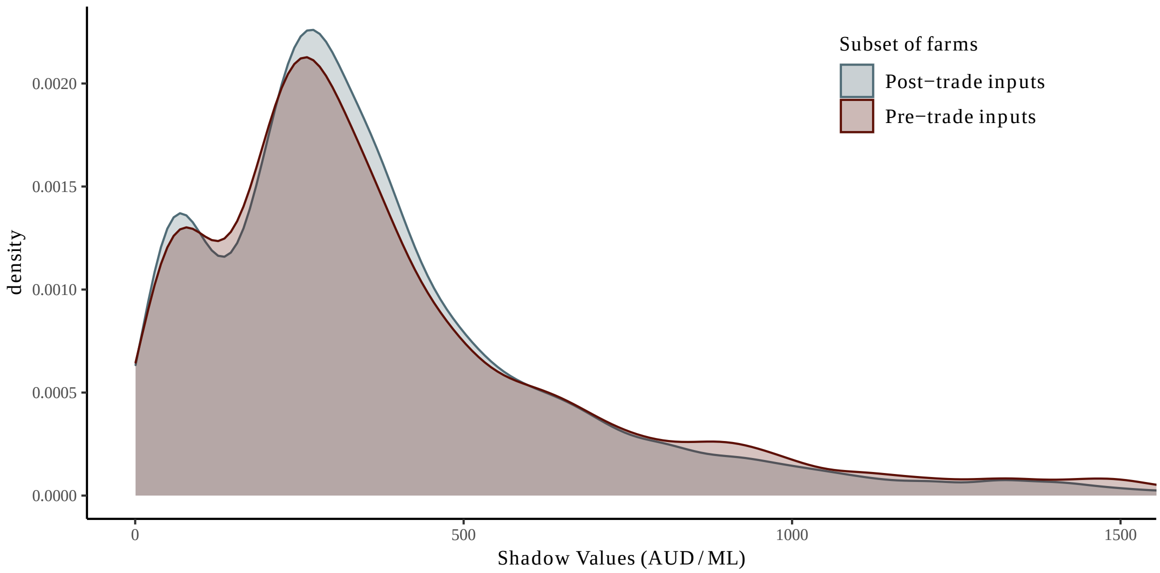


Figure A9. Post-Trade Shadow Value Distribution v. Transaction Prices

Conditional probability densities (top) and CDF (bottom) of farm-crop-level shadow water values at observed inputs (blue) and transaction prices (red), both from 2008–2015; 2007 predates water-price-transaction-level reporting. The x-axis range is 0 to the 97.5%-ile shadow value observation. Nonparametric densities obtained using a Gaussian kernel estimator with a Silverman (1986) optimal bandwidth.

A. All years



B. Drought only (2007–2010)

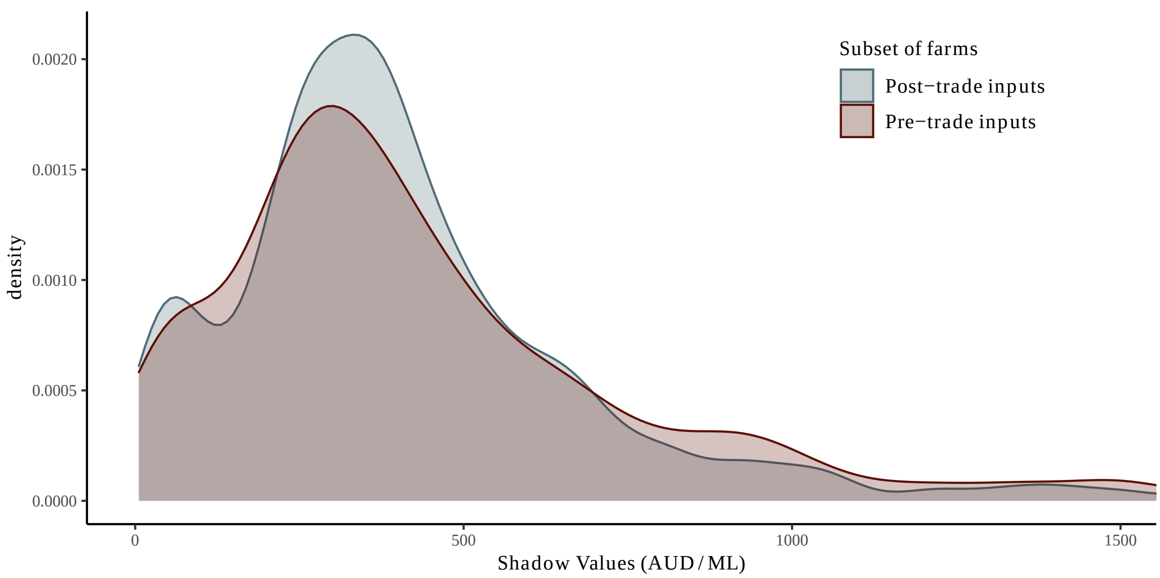
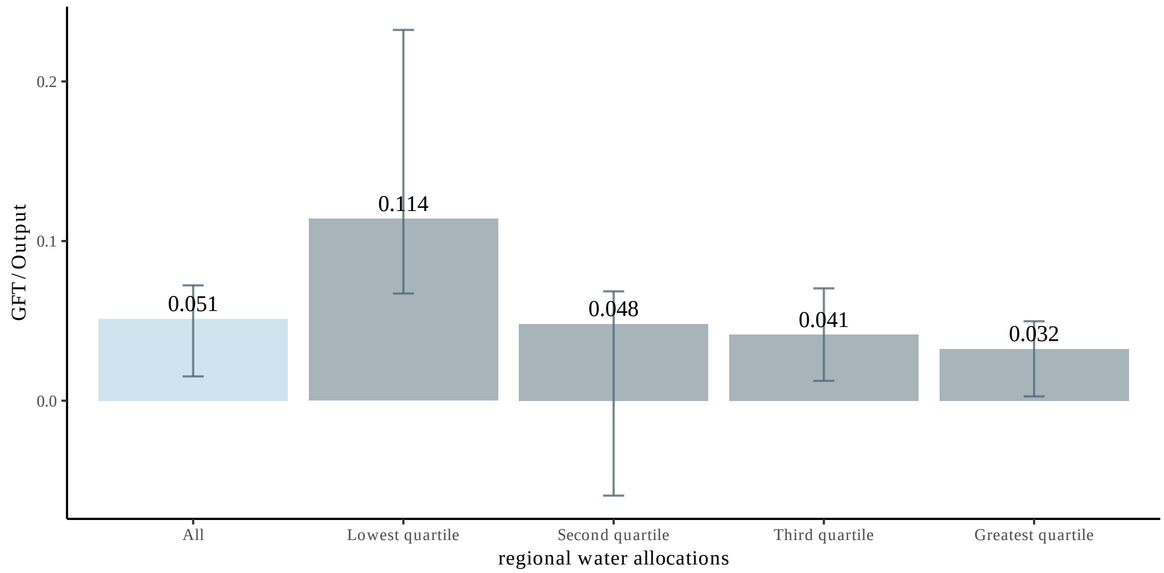


Figure A10. Effect of Trade on Shadow Price Dispersion

Nonparametric densities of estimated farm-crop-level shadow water prices evaluated at observed inputs (blue) and pre-trade inputs (red), for 2007–2015 (top) and 2007–2010 (bottom). The x-axis range is 0 to 97.5%-tile observation. Nonparametric densities obtained using a Gaussian kernel estimator with a Silverman (1986) optimal bandwidth.

A. Regional Water Scarcity, $\overline{W}_{rt}$



B. Farm-Level Rainfall, E^R_{it}

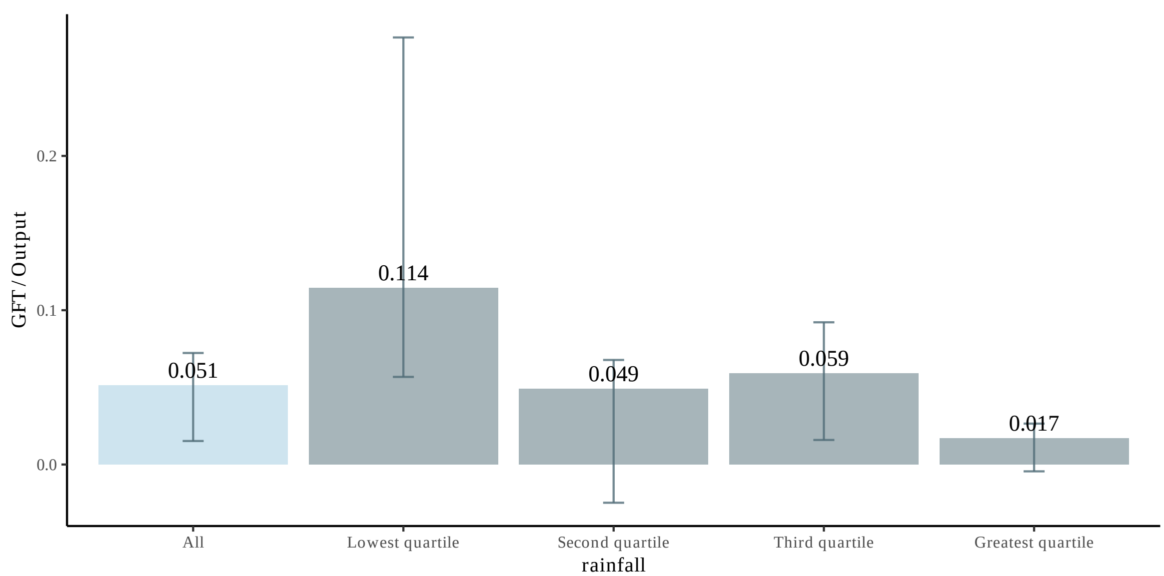
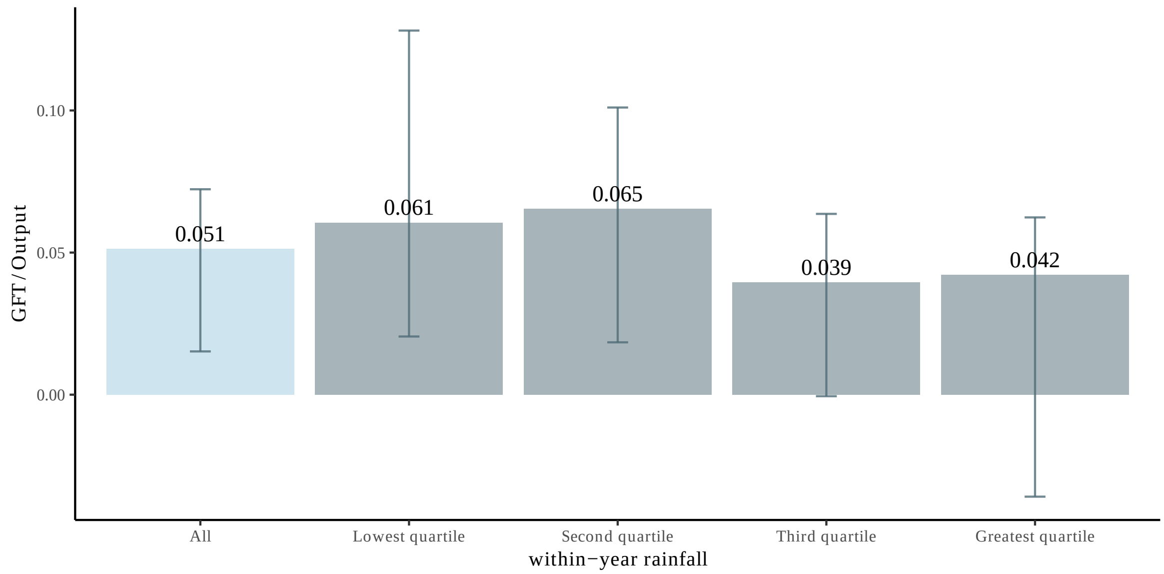


Figure A11. Water Scarcity and the Gains from Annual Trade

Visual depiction of column (1) from Table 6.

Whiskers denote 90% reverse percentile bootstrap confidence intervals from 5000 draws block-bootstrapped at the farm level.

C. Within-Year Differences in Farm-Level Rainfall Across Farms, E^R_{it}



D. Within-Farm Differences in Rainfall Across Years, E^R_{it}

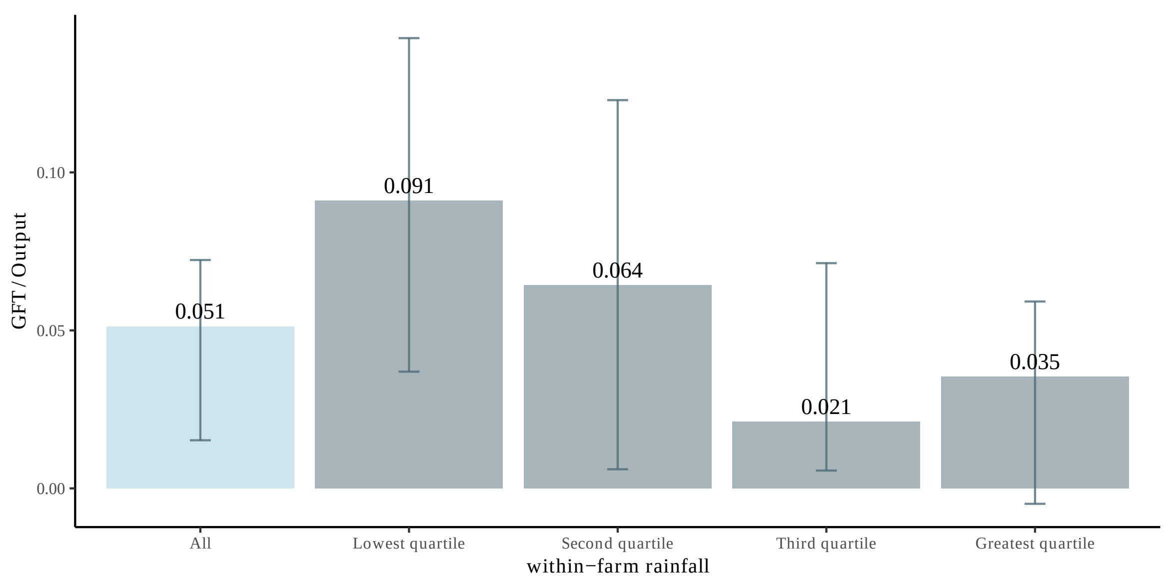


FIGURE A11 (CONT'D). WATER SCARCITY AND THE GAINS FROM ANNUAL TRADE

Whiskers denote 90% reverse percentile bootstrap confidence intervals from 5000 draws block-bootstrapped at the farm level.