Water markets’ promise: the Murray–Darling Basin

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Abstract

The very advanced and well-designed water markets in the Murray–Darling Basin are the result of long and complex reforms. Using state-level export data for agricultural and manufacturing sectors, we study the impact of water markets on the allocation of water through the first (1994–2006) and second reform periods (2007–2015), relative to when the markets’ foundations were laid (1988–1993). We find water markets trigger a shift away from the water-intensive (less water-productive) sectors that is most pronounced during droughts in the first reform period. However, improvements in technology and techniques that reduce water intensity (increase water productivity) partially offset such a shift. We also document an inter-sectoral shift of activity between agriculture and manufacturing, as well as address some recent criticisms of water markets’ effectiveness.

The human appropriation of freshwater has reached the limits of the natural availability in many places. Recent crises in India, Australia, and California underscore the time of water abundance is over (Vörösmarty \textit{et al} 2000, Zetland 2011, Jaeger \textit{et al} 2017). About 3.1 billion people are projected to suffer from water scarcity by 2050 (Gosling and Arnell 2016). Excessive depletion of rivers, lakes, wetlands, and aquifers is undermining the hydrologic conditions to sustain ecosystems (Richter \textit{et al} 2012, Brauman \textit{et al} 2016). We need better ways to reconcile ecosystems’ water needs with those of society. Inevitably, to sustain economic growth while limiting overall water use, requires increased economic productivity of water (Debaere and Kuerzendoerfer 2017, Debaere 2014, Gleick 2018, Marston \textit{et al} 2018).

To notch up water productivity and realize water-neutral growth, societies need to improve water management with new policy tools. Water markets are an increasingly popular tool in water-scarce Australia, Chile, the western United States, and China\textsuperscript{4}. We study the impact of the world’s most advanced water markets in Australia’s Murray–Darling Basin (MDB) on water allocation across sectors, and hone in on changing techniques/technology induced by water markets, which is largely absent from the empirical literature.

Water has both private and public dimensions. It is part of an ecosystem and contributing beyond private consumption (for economic perspectives on water, see Hanemann 2005, Garrick \textit{et al} 2020). Water markets are hence especially defined by policy and political contexts (Teytelboym 2019, Debaere 2020, Garrick \textit{et al} 2020) and require constant design adaptations and improvements: more homogenous rights, less transactions costs, and limited externalities are critical for their proper functioning. Different types of water rights are traded as leases, sales, options, etc, and transactions are governed by (changing) regulations, with varying effectiveness. History illustrates how political and hydrological contexts and our evolving understanding codetermine

\textsuperscript{4} For surveys and broad assessments of water markets, see Chong and Sunding (2006), Grafton \textit{et al} (2011), Grafton \textit{et al} (2012), Debaere \textit{et al} (2014), and Griffin (2016). Garrick \textit{et al} (2013) discuss water markets history. Pioneering are Vaux and Howitt (1984), Howe \textit{et al} (1986), and Colby \textit{et al} (1987). Easter \textit{et al} (1998) provide case studies, is a global update. Schmalensee and Stavins (2017) survey the cap-and-trade literature, water quality trading.
markets’ establishment and design. Operationalizing MDB’s markets was a major policy intervention and a painstaking, unpredictable political process involving states and the central government, with compromises and setbacks.

Water markets are cap-and-trade systems for renewable natural capital through which water rights are bought and sold independent of land titles, see Teytelboym (2019). With an explicit cap on overall water withdrawal, they have the potential to protect rivers’ environmental flows 5. Water markets promise resilience, and flexible and decentralized responses to climate and drought shocks. Water is often priced too low, which induces overuse and discourages innovation and (private) investment in water-saving technology 6. By putting a price on water at the upstream extraction stage, water markets ensure more realistic prices downstream.

Most importantly, water markets can improve water’s allocation and overall productivity. We investigate this critical hypothesis. Market exchanges are expected to shift production to higher-value (less water-intensive) uses, since more productive users can pay a higher price 7. Moreover, water prices incentivize water saving and more efficient irrigation systems. While droughts or command and control measures encourage more productive use of water as well, markets should amplify this productivity benefit since trades additionally make reallocating water across agents possible. To be explicit, since water markets typically operate in water scarce areas, the increase in more productive uses of water they bring about, does not necessarily imply a net reduction in water use, unless the (binding) cap on water use is explicitly reduced.

The MDB provides a unique setting to study the productivity impact of water markets:

- Water markets are complex. Participation in their operation is impeded by uncertainty, information asymmetry (Chokri and Khana 2005), non-competitive behavior (Hantke-Domas 2017), local protectionism (Hagerty 2019), transaction costs (Regnaq et al 2016), and credit constraints (Donna and Espin-Sanchez 2021). Even the harder to measure hydrological, regulatory, and socioeconomic or political context may explain why markets do not emerge everywhere (Garrick et al 2013, McCann and Garrick 2014). Markets’ particular design features are critical (Teytelboym 2019). Since the MDB markets are among the world’s best-managed with well-defined property rights, low transaction costs, ever-improving trading platforms and governance, they are an ideal testing ground to study whether shifting away from more water-intensive activities is in fact possible.

- Australia has faced droughts with drastically reduced water availability and skyrocketing water prices. Droughts should make agents with multiple operations apply scarce water to the higher-value (less water intensive) portion of their activities. Studying the MDB before and after its water market reforms lets us separately identify the impact of markets that additionally promote agents to trade.

- Australia’s MDB markets are some of the largest. Annually, 2 billion Australian dollars are traded, with up to 60% of irrigators participating and redistributing up to a quarter of water for human use (Quentin et al 2011, Department of Agriculture and Water Resources 2016).

- Finally, MDB water markets extend beyond agriculture as cities and utilities participate (Wheeler et al 2014a, 2014b, Horne and Quentin Grafton 2019). The MDB can reveal whether water markets indeed facilitate inter-sectoral shifts away from water-intensive agriculture to industry generating far more dollars per unit of water. Inter-sectoral water allocations are critical to limit water use in growing economies (Debaere and Kuerzendoerfer 2017).

Rather than use production data, we investigate with export data whether the 18 agricultural and manufacturing sectors in Australia’s eight states and territories show a shift away from the more water-intensive activities since 1988. We prefer export data since they are more granular for state manufacturing subsectors, available for longer periods, and easily combined with our water-intensities. Needless to say, we control for the determinants of exports.

Our analysis concentrates on four core MDB states and territories with active markets. We track their changing exports in terms of water intensity as markets are rolled out relative to the initial benchmark period, 1988–1993. Comparing MDB states with non-MDB states confirms our key findings, see appendix A.8 We are mindful of the potential endogeneity of sectors’ water-intensity as higher

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5 Water markets provide a mechanism to buy water to be left in the river, and increase river flow irrespective of the cap. They sometimes allow for a supervising authority to set the amount of water available for use within the cap in a given year or season, depending on the prevailing climate conditions.

6 For surveys of water-pricing policies, see Schoengold and Zilberman (2007), Dinar et al (2013), Quentin et al (2020). Olmstead (2010) emphasizes price adjustments.

7 For water misallocation under water rights regimes, see Libecap (2011). Debaere and Tianshu (2020)'s theoretical setup and assumptions show how water markets can shift water toward, on average, less water-intensive activities.

8 While non-MDB states are not randomized controls for MDB states, it is important to emphasize that when including non-MDB states, our identification hinges on the reasonable assumption of a common trend before water markets are established across MDB and non-MDB states for sectors with similar water intensities, for which we provide support see appendix A.
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Figure 1. Annual numbers of water allocation trade (lease) and water entitlement trade (sale) cases in the southern MDB. Source: Australian Bureau of Agricultural and Resource Economics (1987–2015).

Unit: # of transactions

- Water markets induce a shift toward less water-intensive (more productive) activities that is pronounced during droughts in the first reform. For every decrease in water use of 100 l per Australian dollar (increase in productivity), there is with water markets an increase of a sector’s export share of 0.11 percentage point in droughts. On an annual basis, and relative to the pre-reform dry baseline, markets reduce water use per dollar by 8.25%.
- As we instrument the water intensities with US data, we document how lower water intensity (higher productivity) induced by water markets reduces the need for sectoral reallocations by three quarters.
- A two-sector specification for aggregate agricultural share confirms an inter-sectoral reallocation from agriculture to higher-value manufacturing, irrespective of droughts.
- Estimates within agriculture in the MDB show water markets increase the share of less water-intensive crops exported during droughts. However, in wetter years more water-intensive exports tend to increase. This finding dovetails with ongoing concerns about the efficacy of water-market reforms, as voiced by Young and McColl (2005), Young (2014), and Horne and Quentin Grafton (2019). Markets that price water change people’s behavior and increase water use in spite of a cap. Water may be intercepted, dams built, and previously unused water rights (the so-called ‘sleeper rights’) are being used.

Water prices will induce water saving technology, an issue we address with instrumental variables (IVs) below. It will allow us to gauge how market-induced changes in water-use techniques/technologies alter water’s allocation. For more details, see appendix B.

To do justice to the complex design, establishment, and operation of water markets and their broader impact, we choose a long period (1988–2015) and study their impact on economic activity (exports), rather than study water market transactions themselves or narrower policy interventions in those markets. We distinguish three phases with key legislation, while using the earliest one as benchmark. Following the National Water Commission’s (NWC) timeline, the years up to 1993 lay the institutional groundwork; the first reform period (1994–2006) establishes the basic market infrastructure as markets emerge and expand; finally, the second reform period (since 2007) pushes sustainability. We want to capture the overall impact of the major policy interventions that establish water markets. This will include conservation efforts, water pricing policies by utilities or other downstream adjustments that emerge with water markets, and even governmental water rights purchases to increase river flow. Figure 1 shows how different the reform periods are in terms of transaction volumes of temporary and permanent rights in the southern MDB markets.

Our results reflect a nuanced assessment of the MDB water markets’ impact.
1. MDB water-market reforms

Australia’s water markets story is primarily that of the MDB, where 90% of trading takes place (NWC 2011). The history of this water-scarce continent is intimately linked to water management. With a climate prone to droughts, Australians realized early on that storage and irrigation were key for regional development. Governments focused primarily on the supply side, investing in dams, irrigation systems, weirs, etc. MDB’s water markets moved away from engineering and water supply interventions. According to the NWC, they were meant to facilitate ‘the economically efficient allocation of water while ensuring environmental sustainability’ (NWC 2011, p 8). The MDB fits key preconditions for a successful market:

- MDB’s water is fully developed, which should support reallocating valuable water to higher-value uses.
- Water availability varies seasonally. Water users have varying water demands and varying flexibility to respond to water shortage, making reallocating water desirable.
- Increasing demand for urban and environmental water keep up the pressure to reform and facilitate water reallocations (NWC 2011, p 108).

The MDB covers 14% of Australia’s landmass (see figure 2), and spans over 1000 km of the east coast. Irrigation water is directly extracted along the River Darling, whereas irrigation systems dependent on the Murray are fed by water from behind storage dams (Horne and Quentin Grafton 2019, Hanemann and Young 2020). The basin covers New South Wales, Victoria, South Australia, Australian Capital Territory, and a small fraction of Queensland.

Until the 1970s, states issued water rights (non-priority licenses) virtually on demand; unlike the United States, Australia abandoned riparian and prior appropriation (by seniority) allocations in favor of a non-priority permitting system (Tisdell 2014, Hanemann and Young 2020). Initially water rights were attached to land titles and based on the area of irrigable land. With limited metering and enforcement, irrigators used water generously. By the 1980s, surface and groundwater had been overdeveloped, and maintaining and building dam and irrigation projects became prohibitively expensive. Toxic algal blooms and increasing salinity testified to the deteriorating water quality, as did the loss of native aquatic plants and animal species. The tragedy of the commons was

9 Water markets have specific hydrological, legal, political environments, making comparisons beyond high-level or institutional settings difficult.

10 The MDB Authority website www.mdba.gov.au/water-management/managing-water/water-markets-trade. The Dept of Agriculture, Water and Environment give current information via www.agriculture.gov.au/water/markets. Overviews are found in Herberger (2011), Debaere (2012), Wheeler (2014), Garrick (2015), and Horne and Grafton (2019).
on full display. The MDB started the difficult process of introducing water markets. Water withdrawal had to be limited, water rights redefined, and a trading infrastructure with rules, enforcement, and more uniform governance put in place. The MDB water markets result from a long process and major regional and central initiatives to design an integrated and sustainable water management system.

The NWC distinguishes three critical market design phases. The time line and time span illustrate markets are dynamic, and at the confluence of technical, legal, governance, and political issues that are hard to disentangle. Hence, we assess markets’ impact on the economy (exports) by comparing the three phases:

- **Benchmark: emerging water markets (till FY 1993).** Tentative steps made water markets possible without being part of a grand plan to develop the markets we now have. A moratorium on new water licenses was put in place, and existing permits were redefined in terms of water extraction instead of area, which effectively capped water use, albeit at prevailing levels. There was limited intra-water district trading that allowed access to water for new users without new licenses. Water and land rights were split, lowering transaction costs (NWC 2011, pp 33–42, Horne and Quentin Grafton 2019, pp 177–8).

- **First reform period: expanding water markets (FY 1994–2006).** The 1994 Council of Australian Governments (COAG) Water Reform Framework created a comprehensive system of well-defined water rights, called water entitlements (permanent rights) and water allocations (temporary rights depending on annual assignment of available water to entitlements)\(^\text{11}\). The 2004 National Water Initiative reinforced the COAG reforms and minimized trading costs. Improved information flow (with intermediaries), water rights registration, and better accounting, plus proper regulation of trades and enhanced trading platforms, were developed. Trading of temporary allocations (leases) took off, whereas exchanges of permanent entitlements or across states remained restricted (NWC 2011, pp 44–69, Horne and Quentin Grafton 2019, pp 177–8).

- **Second reform period: transition to sustainable markets (since FY 2007).** The 2007 Water Act anchored

\(^{11}\) An advantage of Australian vs US markets is that entitlements are not defined as absolute volumes, but rather as fractions of the available water. This simplifies distributing water across rights in water-scarce years (Hanemann and Young 2020).
The controversial MDB Plan aimed to reduce and cap water use. Major disagreements among MDB states and tensions between environmentalists and irrigators followed\textsuperscript{12}. The Australian government committed funds to buy back permanent rights for environmental purposes (i.e. leave water in river), and for investing in water-saving irrigation. The central government played a prominent governance role. Trading and market rules improved and became consistent across MDB, facilitating market development. There were efforts to unbundle rights beyond water entitlements and allocations (including delivery rights), and ease interstate trading. In 2009, the Millennium Drought came to an end (NWC \textit{2011}, pp 70–96, Horne and Quentin Grafton \textit{2019}, pp 177–8).

The MDB markets are a major accomplishment. Looking back, it would indeed have been better if all design features had been clear from the outset (Young \textit{2014}). Unresolved issues remain affecting the ecosystem and socio-political context (Horne and Quentin Grafton \textit{2019}). They must be addressed to avoid compromising markets’ proper functioning: water rights for indigenous people, sleeper rights (dormant water rights), occasional lack of enforcement, and incentives to intercept water. We focus on markets’ economic impact. While we expect reforms push economic activity toward less water-intensive uses, some changes (i.e. improved irrigation efficiency and sleeper rights) may pull in the opposite direction.

2. The data

We focus on Australia’s states and territories. We mainly consider the four MDB states and territories with developed water markets: New South Wales, South Australia, Australian Capital Territory, and Victoria. Here, water markets cover over 25% of all land use (see figure 2). Note that we group Queensland into the non-MDB group, since its water markets occupy only 3% of land use with economic activities\textsuperscript{13}.

Table 1 displays huge variation in water intensity. The data come from the Australian Bureau of Statistics (ABS) and the Food and Agriculture Organization (FAO). Water intensity is the ratio of a sector’s liters of direct water use over its production value in Australian dollars. (Water intensity is \textit{not} water per ton, the physical metric common in the sciences.) The inverse of our measure captures water productivity. The intensities are constructed with national (MDB and non-MDB states) production and water use data, and expressed in 1993 real values. Appendix B provides more details. The bold-faced entries give aggregate intensity measures for MDB states, non-MDB states, and overall manufacturing or agriculture. Agriculture’s water intensity is an order of magnitude larger than in manufacturing.

Table 1 also displays water intensities for aggregate exports at the national level (state-specific intensities are not available). There is significant heterogeneity within agriculture. By contrast, intra-manufacturing variation is minor. There is a steady decrease in water intensity (increase in water productivity). Water intensity is cut in half for manufacturing, yet reduced 4.5 times for agriculture.

Even though our water intensity measures come from national data, there is legitimate concern that because of the sheer size of MDB they may endogenously respond to water markets’ higher water prices that trigger water saving efforts. We therefore rely on the comparable US water intensity data as IVs for the Australian measures. While the US data are clearly correlated with Australia’s, they will not be affected by the MDB water market reforms. Doing so allows us to assess Australia’s path relative to that of the US (another major agriculture exporter). See appendix B for details on US water intensities and IV procedure.

Droughts are critical to our analysis. We construct drought measures with state-level annual precipitation data. We draw on the 10 000+ active stations from the Bureau of Meteorology between 1901 and 2016. We selected 5656 stations that overlap with a region’s economic land use in 1992/93 (the last pre-reform year with available land use data) and constructed a balanced panel to capture the effect that corresponds to the pre-reform distribution of economic activities. For those stations, we calculate the pooled state average of annual precipitation.

To identify drought in a state over time, we use a 0/1 indicator. With different climates across states and relatively high within-state standard deviation in Australia’s precipitation, we assess droughts relative to a state’s historical precipitation. A dry spell is a period of low rainfall when last 2 years falls within the lower 25th percentile of state precipitation throughout the entire 20th century\textsuperscript{14}. Figure 3 visualizes droughts across all states. To separately identify water markets’

\textsuperscript{12} The upstream MDB states were reluctant to reduce water use and pushed back against too much water for the environment, reducing water targets, see Horne and Quentin Grafton (2019).

\textsuperscript{13} Land use data come from \textit{Land Use of Australia, Version 3 1992/93} (the last pre-reform FY) by Australia’s Bureau of Rural Sciences. The water market coverage is digitized from figure 2.1 in the NWC’s \textit{Australian Water Market Report 2008–09}.

\textsuperscript{14} In terms of demeaned and standardized precipitation \((P − \bar{P})/\sigma\), our dry conditions require a negative value that is smaller than \(-0.675\) pooling two subsequent years. To be clear, our drought cutoff (with annual data) is both looser and tighter than the value of \(-1\) that is sometimes used. On the one hand, we require dry conditions for two subsequent years. Since we are dealing with the Big Dry in the MDB, we need some persistence in dry conditions of the control periods and control states. On the other hand, also because of Australia’s relatively high standard deviation of within-state annual precipitation (25% above within US states), we allow for a slightly less stringent cutoff (\(-0.675\)). With this cutoff we have dry spells before and after water markets are introduced, both in \textit{and} outside the MDB.
Table 1. Water intensity in Australia.

| Item code | 1988–93 | 1994–2006 | 2007–15 |
|-----------|---------|-----------|---------|
| Agriculture | 100    | 984.3     | 489.1   | 228.9   |
| Apple and pear | 102    | 719       | 480     | 352     |
| Cattle and calves | 104    | 449       | 240     | 143     |
| Eggs | 106    | 159       | 92      | 71      |
| Grain | 107    | 1574      | 656     | 327     |
| Grape | 108    | 1423      | 764     | 552     |
| Pigs | 110    | 744       | 416     | 364     |
| Poultry | 111    | 2362      | 1385    | 316     |
| Sheep and lambs | 112    | 1552      | 429     | 163     |
| Stone fruits | 113    | 961       | 639     | 538     |
| Vegetable | 115    | 490       | 327     | 235     |
| Manufacturing | 200    | 4.1       | 3.9     | 2.3     |
| Food, beverage, and tobacco | 201    | 3.5       | 4.2     | 4.0     |
| Textile, clothing, footwear, and leather | 202    | 7.8       | 6.7     | 1.4     |
| Wood, paper products and printing, publishing | 203    | 8.2       | 7.3     | 4.0     |
| Petroleum, coal, chemical, and associated products | 204    | 2.3       | 2.2     | 1.3     |
| Non-metallic mineral products | 205    | 2.7       | 2.8     | 2.0     |
| Metal products | 206    | 6.1       | 5.7     | 2.6     |
| Machinery and equipment | 207    | 0.8       | 0.7     | 0.3     |
| Mining | 300    | 18.3      | 16.2    | 4.4     |
| Australia average | b | 213.4     | 52.1    | 17.3    |
| MDB states average | b | 249.9     | 52.6    | 22.0    |

Note: a Denominator in 1993 real values.  

b Weighted by annual export value.

Impact on exports from that of droughts, we must obtain dry and wet spells in all NWC phases of the evolving MDB markets.

The sectoral state export data stem from ABS and are classified by three-digit Australian and New Zealand Standard Industrial Classification (ANZ-SIC). We focus on agriculture and manufacturing that are most affected by water markets. (Mining typically has its own water supply.) For each state, we consider sectors’ export share in total (manufacturing +
agricultural) exports. Australia is about twice as open as the US, exporting over 20% of its GDP in recent years. About 70% of agriculture (using the majority of water) is exported (Australian Government 2021).

To capture global factors that affect Australia’s exports, we include the total world-level sectoral imports (excluding Australia) from country-level UN Comtrade imports from 1988 to 2015 (https://comtrade.un.org/Data/). We manually match the commodity codes based on the ANZSIC in our sample with Comtrade’s Harmonized System. We, however, have no good measure to control for domestic demand should it deviate from international trends for certain goods. From 1995 onwards we rely on ‘use’ (exact name in statistics) in more aggregated industries from ABS (www.abs.gov.au/statistics), which captures the domestic market. We linearly inter/extrapolate missing years.

Some of our regressions include state-level production factors that are common in regressions explaining states’ international trade. These factors capture states’ endowments. Annual state-level employment and capital stock data come from ABS.

Finally, we also use two state-level measures of heating degree days (HDDs). We use the 5656 + stations mentioned above, again calculating pooled state averages. One measure is the cumulative sum of days with average daily temperature above 8 °C, while the other of days above 32 °C; Deschênes and Greenstone (2007) define degree-days in this way based on the standard agronomic approach. We include both current and lagged precipitation and HDDs because harvested crops in a year could have been growing over the previous year. Appendix table 1A reports summary statistics.

3. The specification

Our basic specification explains Australia’s sectoral export shares, which vary across states and territories and over time. We focus on the four MDB states and territories (and extend to comparison with other states in appendix A). Equation (1) determines whether the two reform periods changed the export structure in the MDB relative to the initial benchmark. We wonder whether the share of more water-intensive exports decreases relative to that of less water-intensive ones, while controlling for year effects, state × industry effects, and many additional variables. We cluster standard errors at the state-level:

$$\text{ExportShare}_{sit} = \alpha_i + \alpha_{si} + \beta_1 \text{Reform}_I ⊗ \text{WaterIntensity}_{sit} + \beta_2 \text{Reform}_II ⊗ \text{WaterIntensity}_{sit} + \beta_n \text{State}_{sit} + \epsilon_{sit}. \quad (1)$$

ExportShare$_{sit}$ captures the share of state $i$’s sector $t$ in the state’s overall manufacturing and agricultural trade for year $t$. The critical coefficients are $\beta_1$ and $\beta_2$.

A negative sign indicates reforms decrease the share of more water-intensive goods exports in the MDB. Since there are zero-value observations for exports, we avoid logs. We insert a whole series of controls under $X_{sit}$, including state precipitation, HDDs, the logarithm of state labor force and capital stock. We also include the shares of excluded sectors15. The fixed effects capture many factors that are difficult to specify but stay constant. Year fixed effect absorb common events across MDB states, whereas industry-state effects take into account state-specific industry components. With the year-fixed effects, we cannot assess the impact of changing the fraction of a state’s water that is allocated within the cap due to changing water availability conditions. Since industry water intensities vary at the national (not state) level, there is not enough variation to include industry-year-fixed effects that would capture sectoral movements, especially in world markets. We therefore include sectoral global exports that change over time. Since MDB states are relatively similar (and water intensities do not vary by state), our preferred specification has no state-year-fixed effects and exploits the temporal variation of water-intensive versus less water-intensive sectors across the MDB

16. Since the overall size of exports varies significantly across states, we weight our estimates by state-level average total annual export values pooling all pre-reform years.

We investigate whether water markets respond flexibly to shocks. Therefore, we run additional regressions with interactions with our drought indicator: $\beta_1 \text{Reform}_I ⊗ \text{WaterIntensity}_{sit} ⊗ \text{drought}_{sit}$ and $\beta_2 \text{Reform}_II ⊗ \text{WaterIntensity}_{sit} ⊗ \text{drought}_{sit}$. We include the drought indicator and other corresponding double interaction terms of drought separately. We also consider similar specifications for the agricultural sector only.

Given the complexity and unpredictable nature of establishing water markets, the endogeneity of the reform periods is not a concern. Establishing water markets has been a very slow, time-consuming, political and unpredictable process. There is, however, some concern the national water intensity measures may respond to water markets, since the MDB is an important water user. Indeed, higher water prices should incentivize decreasing the water intensities. We instrument Australian water intensities with their US counterparts; see below.

4. Discussion

The columns of table 2 capture the coefficient estimates of our regressions. The first four rows of estimated coefficients let us compare the water

15 For example, when focusing on agriculture, we include manufacturing as control.

16 The results are qualitatively similar with state-year-fixed effects, see appendix table 4.
market impact of the first and second reforms relative to the benchmark period across the various regressions. (The other rows refer to other controls and fixed effects that are (not) included in the specifications). The first two columns show the IVs results with US intensities instrumenting for Australia’s. Columns (3) and (4) give the ordinary least squares (OLSs) estimates, which allow for endogenous responses in water-saving technology techniques following market reforms.

A few observations stand out. Consider the IV estimates. We obtain negative and statistically significant coefficients for both reform periods in the specification without drought. With a water market in place, there is a 0.15–0.16 percentage point decrease in sectors’ export share for every 100 l increase per dollar. When we bring in the interaction with drought, a negative, statistically significant coefficient is estimated only for the dry years in both periods, leaving wet periods insignificant. The establishment of the water markets in the MDB (with IVs) thus would have induced a shift away from the more water-intensive exports, especially in dry years, if the MDB had not adapted its water-use technology techniques following the market’s establishment.

Comparing IV and OLS coefficients is instructive. With or without drought interactions, we obtain negative coefficients for both periods. Interestingly, and this is consistent for our drought estimates, the negative OLS coefficients are smaller than the IV estimates. As we report later, some OLS estimates may even be of the opposite sign (positive). An interesting interpretation offers itself. The endogenous adaptation to water markets (higher water prices), mitigates the need to shift export shares away from water-intensive sectors. This result is intuitive, since changing the sectoral composition entails frictions. Especially more water-intensive sectors reduce their water use. Our estimates corroborate table 1’s raw data.

Our results so far confirm our earlier findings of Texas water markets’ shift toward less water-intensive activities (Debaere and Li 2020). In addition, we now account for technological adaptation, because our water use measures are not based on biophysical water absorption of crops. Our present analysis casts a richer, more nuanced light on water markets’ impact.

Figure 4 complements table 2, and checks whether our estimates feed off of pre-existing differential trends before the water markets. Figure 4 provides annual estimates in MDB states of water markets’ impact. We plot the coefficients of the double interaction of water intensity and yearly dummies (instead of \( \beta_1 \) and \( \beta_2 \) of specification (1)). Since the graphs should document water markets’ impact on sectoral shifts, we present yearly estimates with US water intensity measures that do not endogenously respond to Australia’s reforms. As we stretch the data with annual estimates, we obtain more insignificant coefficients. Even so, the negative impact of the reforms compared to the benchmark year (1988) is clear, especially for dry years (marked for MDB states).

Table 2. The effect of water market reforms on state-level export shares in MDB states.

| Variables                      | IV: US water intensity | OLS results |
|--------------------------------|------------------------|-------------|
|                                | (1)                    | (2)         | (3) | (4) |
| Period (94–06)                 | −0.148*                | −0.101      | −0.085** | −0.026 |
| \( \times \) Water intensity\* | (0.076)                | (0.085)     | (0.024) | (0.022) |
| Period (07–15)                 | −0.155***              | −0.026      | −0.239*** | 0.097 |
| \( \times \) Water intensity\* | (0.011)                | (0.046)     | (0.011) | (0.045) |
| Period (94–06) × Drought\*     | —                      | −0.502***   | —     | −0.107*** |
| \( \times \) Water intensity\* | (0.069)                | —           | —     | (0.030) |
| Period (07–15) × Drought\*     | —                      | −0.867***   | —     | −0.249*** |
| \( \times \) Water intensity\* | (0.136)                | —           | —     | (0.029) |
| Industry-year control variables\* | Yes                    | Yes         | Yes | Yes |
| State-year control variables\* | Yes                    | Yes         | Yes | Yes |
| State \( \times \) industry and year-FE’s | Yes          | Yes         | Yes | Yes |
| Other interactions terms\*     | —                      | Yes         | —    | Yes |
| Observations                   | 1844                   | 1844        | 1844 | 1844 |
| Number of states \( \times \) industries\* | 68                       | 68          | 68   | 68  |

Note: * Period (94–06)’ and ’Period (07–15)’ are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period);’water intensity’ in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).  
\( ^b \) Drought’ is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.  
\( ^c \) ’Industry-year control variables’ includes water intensity and the logarithmic value of world total import (except Australia).  
\( ^d \) ’State-year control variables’ include export share of mining, logarithmic values of employment and capital stock, the drought dummy, and weather controls for the current and previous years including precipitation, HDDs above \( 8^\circ C \) and above 32 \( ^\circ C \), respectively.  
\( ^e \) ’Other interaction terms’ include ’Period (94–06) × Drought’ and ’Period (07–15) × Drought’ for Columns (2) and (4).  
\( ^{f} \) Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses, \( ^{∗∗∗} p < 0.01, ^{∗∗} p < 0.05, ^{*} p < 0.1 \).
In Table 3, we analyze manufacturing’s role (a non-agricultural sector), before discussing the impact of water markets within agriculture and addressing lingering environmental criticisms.

We aggregate all manufacturing and all agricultural subsectors respectively, and investigate agriculture’s overall share in the state-by-year panel of Table 3. To alleviate concerns about the common trend assumption between MDB and non-MDB states, we apply a synthetic control approach in Columns (3) and (4), which corroborates the robustness of Columns (1) and (2). We obtain significant, negative coefficients after the first-round reform. This illustrates an inter-sectoral shift away from (aggregate) agriculture to manufacturing irrespective of drought. This is intuitive since agriculture uses per Australian dollar, 100 times more water. Based on those huge average differences, one expects also differences in marginal productivity, incentivizing inter-sectoral reallocations. The later reforms also exhibit negative, but statistically insignificant coefficients.

Figure 4. Year-by-year estimates pooling MDB states and all industries.

Note: Coefficients plotted are for the interaction terms of the US water intensity measure and yearly dummies. The benchmark year is 1988. Control variables are consistent with Column (1) of Table 2.

The inter-sectoral movement from agriculture to manufacturing is important. It confirms potential gains from including urban areas, which has not been easy.

Table 4 focuses on agriculture’s subsectors in the MDB. The left part reports IV instruments, the right part, OLS estimates. The IV estimates in Column (2) display the familiar, statistically significant negative coefficient for dry years. This is consistent with Rafey (2020), who also finds the effects of water markets amplified during droughts—Rafey (2020)’s shorter time period perhaps explains why he does not consider technological/technique changes. The coefficient becomes insignificant in OLS (Column (4)) with endogenous technology adoption. It is noteworthy, however, that for non-drought years, we consistently obtain positive coefficients for OLS and IV. This suggests water markets do not induce the expected shift to less water-intensive crops within agriculture compared to the benchmark in wetter years.

The positive coefficients warrant two observations:

- The inter-sectoral shift from agriculture to manufacturing in Table 3 counterbalances the reallocation in agriculture to more water-intensive crops in wetter years. This inter-sectoral movement helps explain why we discern a move to less

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17 The synthetic control approach is used to construct more comparable control group when the treatment group (in our case, the MDB water market states) is small in number and it is difficult to choose comparable controls (Abadie 2021). By using this approach, we ‘synthesize’ a more comparable control state for each MDB state using a specific weighted average of (raw) control states based on pre-reform logarithmic values of employment and capital stock.
The move toward more water-intensive crops supports criticism against water markets. Young (2014) and others caution Australian markets may have increased water use by changing incentives. Irrigators monetized previously un-used sleeper rights. There were attempts to capture water on lands and build small dams that increased the output of water-intensive crops. And there are concerns over the environmental context, and whether markets have lived up to the sustainability promises of the second reform.

Water markets are tools in the fight against water scarcity. They may improve water's allocation, and the

### Table 3. The effect of water market reforms on state-level agricultural export shares (MDB vs non-MDB).

| Variables | (1) | (2) | (3) | (4) |
|-----------|-----|-----|-----|-----|
| Period (94–06) × MDB | -5.411** | -5.596* | -5.914** | -6.426*** |
| (1.941) | (2.490) | (1.705) | (1.702) |
| Period (07–15) × MDB | -2.487 | -2.531 | -4.313* | -3.920 |
| (3.355) | (4.921) | (1.903) | (2.467) |
| Period (94–06) × MDB × Droughtb | - | 2.927 | - | 3.242 |
| (1.603) | (1.951) |
| Period (07–15) × MDB × Droughtb | - | 2.644 | - | 0.719 |
| (1.971) | (2.229) |

### Table 4. The effect of water market reforms on agricultural export shares in MDB states.

| Variables | (1) | (2) | (3) | (4) |
|-----------|-----|-----|-----|-----|
| Period (94–06) | 1.19*** | 1.25*** | 0.045* | 0.047* |
| × Water intensityc | (0.326) | (0.316) | (0.015) | (0.016) |
| Period (07–15) | 1.13*** | 1.29*** | 0.362*** | 0.359*** |
| × Water intensityc | (0.093) | (0.157) | (0.025) | (0.033) |
| Period (94–06) × Droughtb | - | -1.89*** | - | -0.033 |
| × Water intensityc | - | (0.174) | - | (0.019) |
| Period (07–15) × Droughtb | - | -2.35*** | - | -0.003 |
| × Water intensityc | - | (0.364) | - | (0.052) |
| Industry-year control variablesd | Yes | Yes | Yes | Yes |
| State-year control variablesd | Yes | Yes | Yes | Yes |
| State × industry and year-FE’s | Yes | Yes | Yes | Yes |
| Other interactions termsd | — | Yes | — | Yes |
| Observations | 1060 | 1060 | 1060 | 1060 |

Note: a Synthetic controls are generated for the MDB states based on pre-reform logarithmic values of employment and capital stock.

b ‘Drought’ is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.

c ‘Other control variables’ include the export share of mining and weather controls for the current and previous years including precipitation, HDDs above 8 °C and above 32 °C, respectively.

d ‘Other interaction terms’ include ‘Period (94–06) × Drought’, ‘Period (07–15) × Drought’, ‘MDB × Drought’, and ‘Drought’.

e Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses,

IV: US water intensity

| Variables | (1) | (2) | (3) |
|-----------|-----|-----|-----|
| Period (94–06) | 1.89*** | 1.89*** | 0.033 |
| × Water intensityc | (0.093) | (0.157) |
| Period (07–15) | 1.89*** | 1.89*** |
| × Water intensityc | (0.093) |
| Period (94–06) × Droughtb | - | -2.35*** |
| × Water intensityc | - |
| Period (07–15) × Droughtb | - |

Note: a Period (94–06) and Period (07–15) are 0/1 indicators for 1994–2006 and 2007–2015, respectively (1988–93 serves as the baseline period); ‘water intensity’ in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

b ‘Drought’ is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.

c ‘Other control variables’ include water intensity and the logarithmic value of world total import (except Australia).

d ‘State-year control variables’ include export share of mining, logarithmic values of employment and capital stock, the drought dummy, and weather controls for the current and previous years including precipitation, HDDs above 8 °C and above 32 °C, respectively.

e ‘Other interaction terms’ include ‘Period (94–06) × Drought’ and ‘Period (07–15) × Drought’ for Columns (2) and (4).

f Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses,

## Note:

- Period (94–06) and Period (07–15) are 0/1 indicators for 1994–2006 and 2007–2015, respectively (1988–93 serves as the baseline period).
- ‘Water intensity’ in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).
- ‘Drought’ is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.
- ‘Other control variables’ include water intensity and the logarithmic value of world total import (except Australia).
- ‘State-year control variables’ include export share of mining, logarithmic values of employment and capital stock, the drought dummy, and weather controls for the current and previous years including precipitation, HDDs above 8 °C and above 32 °C, respectively.
- ‘Other interaction terms’ include ‘Period (94–06) × Drought’ and ‘Period (07–15) × Drought’ for Columns (2) and (4).
- Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses.
production of less water-intensive sectors. Back-of-the-envelope calculations show overall water use per Australian dollar of export dropped by 8.25% annually in droughts when allowing for endogenous technological improvements of the more water-intensive sectors.\(^{18}\)

5. Conclusion

With climate change and ever-growing populations and economies, water-neutral growth is important. Societies have to do more with less. Less water producing more, however, calls for increasing water productivity (decreasing water intensity). Australia’s MDB water markets are some of the largest and most advanced whose establishment and design was long and complex. After initial basic institutional changes, water markets took off during the first (1994–2006) and second reform period (since 2007). We study the broader, more aggregate impact of this significant policy intervention, rather than analyze one (of many) policy interventions during this storied history. To do justice to this intricate history, we assess water markets’ impact on the economic (export) structure of Australia’s states through the various development phases that NWC identified. Our results reflect this complexity and adjusting design features.

Water-market reforms have increased overall water productivity by 8.25% on an annual basis during dry periods. The movement toward higher-value sectors is partly driven by the shift towards less water intensive manufacturing. To our knowledge, we highlight for the first time how water markets induce technology/technique changes that mitigate the need to shift away from water-intensive activities. The reduction in water intensity is especially pervasive for more water-intensive sectors.

Our analysis touches on ongoing environmental criticism of Australia’s water markets concerning overall water use. We see in dry years, a shift in the MDB toward less water-intensive crops that is mitigated by adaptation, which comparisons with non-MDB states confirm. However, we find within MDB’s agriculture a shift toward more (not less) water-intensive activities in wetter periods, a shift that does not entirely disappear when assessed in the context of all of Australia’s agriculture.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Appendix A. Analyses comparing the MDB states with other states

A.1. Data and empirical strategy

As mentioned in section 2 of the main manuscript, summary statistics for variables that we use for the regressions are reported in appendix table 1A. Moreover, in appendix table 1B, we further compare the average of our variables for the MDB and non-MDB states. Overall, the values are similar, except for the non-MDB states’ higher share of mining in total exports and our drought measure.\(^{19}\)

In specification (A1), we extend equation (1) from section 3 to all of Australia. The regression includes the non-MDB states and territories as controls, and hence, the two reform periods are interacted with a dummy for the MDB states and territories. Here also, we cluster the standard error at the state level to address within-state correlations:

\[
\text{ExportShare}_{sit} = \alpha + \beta_1 \text{Reform}_I \times \text{WaterIntensity}_{sit} \\
\times \text{MDB} + \beta_2 \text{Reform}_II \times \text{WaterIntensity}_{sit} \\
\times \text{MDB} + \beta_3 \text{WaterIntensity}_{sit} \times \text{MDB} \\
+ \beta_4 \text{Reform}_I \times \text{WaterIntensity}_{sit} \\
+ \beta_5 \text{WaterIntensity}_{sit} + \beta_6 X_{sit} + \epsilon_{sit}. \quad (A1)
\]

The main coefficients of interest are \(\beta_1\) and \(\beta_2\). Both should indicate whether water markets in the MDB have a discernable impact when compared to other states without water markets. As emphasized before, it is hard to argue that states are random or identical controls for the MDB. For that reason, we have included state-year effects in the regression (and drop control variables that only vary by year and state).\(^{20}\) Thus \(\beta_1\) and \(\beta_2\) capture the triple differences

\(^{18}\) In Column (4) of table 2, an industry’s export share on average decreases by 0.11 percentage point for every additional 100 l per Australian dollar of water intensity (relative to the least water-intensive industry) in drought years after the Phase I reforms. With this estimate we predict the counterfactual export composition for drought years hypothetically in absence of the reform. Combining this counterfactual and the actual export compositions with industry water intensity measures, we can compare their water use. When comparing the water intensity measures under both scenarios, water use per Australian dollar (after Phase I reforms) is 47% of the counterfactual measure without the reform. Thus, reforms nearly double water productivity of exports in droughts. This shift occurred over 9.5 years on average, so in annual rates we get 8.25%.

\(^{19}\) Note that the share of mining in exports uses the overall export value as the denominator to account for the differential importance of mining for each state, whereas the outcome variable—the share of each item in agriculture and manufacturing—uses the total export value only of agricultural and manufacturing sectors as the denominator, to capture the shifts of shares within the two sectors.

\(^{20}\) Note that including only an interaction of MDB and year effects (complementing the specification for the MDB states) makes no qualitative difference, see appendix table 5.
Appendix Table 1A. Summary statistics (# of Obs: 3907).

| Variable                  | Mean  | Std. Dev. | Min   | Max   |
|---------------------------|-------|-----------|-------|-------|
| Share of export           | 5.7   | 12.9      | 0.0   | 100.0 |
| ln(labor employed)        | 7.2   | 1.2       | 4.9   | 8.9   |
| ln(capital stock)         | 13.8  | 1.2       | 11.9  | 15.5  |
| Share of mining           | 26.6  | 28.2      | 0.0   | 93.4  |
| Precipitation             | 757   | 244       | 319   | 1666  |
| Heating degree-days (HDDs)<8 °C | 3619 | 1005      | 804   | 5928  |
| Heating degree-days (HDDs)>32 °C | 4.8 | 7.9       | 0.0   | 47.6  |
| Drought year indicatorb   | 0.2   | 0.4       | 0.0   | 1.0   |
| Log (world import value)  | 24.3  | 2.6       | 11.5  | 29.6  |

Appendix Table 1B. Statistics for MDB states vs non-MDB states.

| Variable                  | MDB state (# of Obs: 1910) | Non-MDB states (# of Obs: 1997) |
|---------------------------|---------------------------|---------------------------------|
|                           | Mean          | Std. Dev. | Mean       | Std. Dev. |
| Share of export           | 5.86          | 12.66     | 5.61       | 13.12     |
| ln(labor employed)        | 7.67          | 1.09      | 6.76       | 1.17      |
| ln(capital stock)         | 14.13         | 1.09      | 13.43      | 1.13      |
| Share of mining           | 8.55          | 11.32     | 43.93      | 28.73     |
| Precipitation             | 678           | 197       | 833        | 259       |
| Heating degree-days (HDDs)<8 °C | 3159 | 550       | 4059      | 1136      |
| Heating degree-days (HDDs)>32 °C | 1.42 | 2.03      | 8.07      | 9.81      |
| Drought year indicatorb   | 0.13          | 0.34      | 0.21       | 0.41      |

of interest in within-state variations among the more and less water-intensive sectors over time by comparing the two groups of states. To be clear, what these two coefficients of interest pick up is not double differences such as the potentially distinct between-state variations in the changes of sectoral composition, but the more comparable within-sector evolutions of similar sectors pooling all states. As a result, the coefficients of β1 and β2 can help indicate whether there are common factors across Australia that may confound any assessment of water markets’ impact on the relative export shares of more versus less water-intensive sectors that is singularly focused on the MDB states.

Note that we also upgrade this second specification to study the specific role of droughts, and include two extra terms in regression (2): β7Reform_I * WaterIntensity * drought * MDB and β8Reform_II * WaterIntensity * drought * MDB, as well as other triple- and double-interaction terms of drought. As before, we also run regression (A1) separately for all the agricultural subsectors.

A.2. Results

In appendix table 2, we consider the impact of the water markets in the context of all of Australia. We bring in the non-MDB states, and exploit the within-state variations among the more and less water-intensive sectors across the two groups of states. We want to see to what extent they corroborate our findings for the MDB only. As is well known, it is possible that Australia-wide shifts in activities between more or less water-intensive sectors (due to, for example, crop price movements or changing preferences) may confound the effect of the water markets, obtained in table 3 that was identified only within the water market states of the MDB.

The inclusion of the non-MDB states in appendix table 2 weakens the overall results. The scale of the coefficients is approximately half of the corresponding numbers in table 2 for the MDB states sample, and we obtain less statistical significance. We focus on our preferred specification, which separates out dry and wet spells. The estimates that stand out especially are those for the first reform period. In dry years, there is a consistent shift toward less water-intensive sectors with and without IV. (For the OLS estimates, there is—even in wet years—a statistically significant negative coefficient.) The second reform period still exhibits a negative, but marginally statistically insignificant, effect in drought years.

In this specification across all of Australia, we see again the importance of the endogenous response to water use. The estimated OLS coefficients here are also much smaller than the IV coefficients, indicating that adaptation has consistently mitigated the need to reallocate economic activity to less water-intensive activities. Without that adaptation, there would have been a much stronger swing toward the less water-intensive sectors.\(^1\)

Appendix figure 1 complements the estimates in appendix table 2 and addresses potential concerns as to whether our estimates feed off pre-existing differential trends from before the water markets were in

\(^1\) In appendix tables 6 and 7 we provide estimates that control for domestic use with our imperfect (extrapolated) measure. Including this measure does not alter our results in an important way.
place. This figure visualizes for all of Australia the corresponding coefficients, meaning the triple interactions of the MDB dummy, the US water intensity, and yearly dummies (instead of $\beta_1$ and $\beta_2$ of specification (A1)). Similar to figure 4 of section 4, we observe mostly statistically insignificant fluctuations before the two rounds of the reforms, but movements towards the negative direction afterwards, especially for the marked-out drought years in MDB states.

Appendix table 3 finally puts the estimation results that we obtained for the agricultural sector in the context of Australia as a whole. When considering the agricultural sectors across all states and territories, there is still a significant effect of water markets in the reform periods on the allocation of agricultural exports toward less water-intensive crops for drought years. Here again, the reallocation with the IVs is attenuated in the OLS regressions that allow for technology adaptation. The estimates for the non-drought years are also of interest, however. In one of the reform periods at least, the IV estimates are no longer significant in the context of all of Australia during wet years, which opens the possibility that part of the shift toward more (not less) water-intensive crops may be a nationwide trend. Perhaps, in a country that experiences frequent droughts, water-saving as well as crop-shifting decisions happen even in the absence of a water market and an explicit price of water. It is noteworthy, however, that the OLS estimates for the first period indicate a significant shift toward more water-intensive sectors in water-market states. This could suggest that adapting irrigation techniques or technology may have pushed agriculture in the water-market states of the MDB toward more water-intensive crops. More detailed micro-analysis will be necessary to settle this debate.

Appendix B. Water intensity measures and the two-stage least squares (2SLSs) methodology

In this appendix we describe the construction of our water intensity measures and the 2SLSs methodology.

In general, the water intensity measures for industry $i$ in year $t$ follow the following equation:

$$\text{Water Intensity}_{it} = \frac{\text{quantity of direct water use}_{it}}{\text{value of product}_{it}}.$$  \hspace{1cm} (A2)

The first two sections detail how we construct the intensity measures respectively for Australia and the United States. Due to data constraints, in our main specification, we use the pooled average for each of the pre-reform (1988–93), first-round reform (1994–2006), and second-round reform (2007–15) periods to generate a full balanced panel of water intensity measures. The last section explains the 2SLSs methodology and the rationale for our IV choice.

B.1. Water intensity measures for Australia

As the numerator of equation (A2), the quantity of direct water use by industry for both agriculture and manufacturing is mainly based on the ‘water consumption’ measures reported in the water account data from the ABS, which is available for 1993–94 to 1996–97, 2000–01, 2004–05, and 2008–09 to 2013–14. When the water account data is not available for some of the crop categories for certain years, we rely on the ‘water applied’ measure reported in the gross value of agricultural commodities (GVCs) by the ABS, and rescale it proportionally based on other overlapping years to match the ‘water consumption’ from the water account.

As the denominator, the value of agricultural products by industry comes from the GVC covering 1988–97 and 2001–2009 and the official data from FAO which contain food prices from 1991 to 2015, values from 1991 to 2013, and quantities from 1988 to 2014. For the few earlier years (1988–93) where ‘water consumption’ cannot be complemented with any of the sources, we assume that the physical water intensity for industry $i$ (quantity of direct water use/quantity of product$_{it}$) is fixed over time, and use the price evolvement to back out value-based water intensity from later years to earlier years, i.e.,

$$\text{Water Intensity}_{it} = \frac{\text{quantity of direct water use}_{it}}{\text{value of product}_{it}} \times \frac{1}{\text{Price}_{it}}$$

For the manufacturing sector, the denominator of equation (A1) is also available at the industry level from the ABS. However, because a suitable weight measure cannot be applied for most manufacturing industrial categories as used in equation (A3), we can only generate the water intensity for 1993–97, 2001, 2005, and 2009–14. Due to the incompleteness in the time series of the water intensity measures for manufacturing, we use the pooled average of water intensity within each of the three periods (i.e. 1988–93, 1994–2006, and 2007–15) in our analysis.

B.2. Water intensity measures for the United States

The quantity of industry-level water use, as the numerator of equation (A2), comes from the ‘water withdrawal’ measure in the US Geological Survey (USGS), which is available every 5 years. We take the data from 1985 to 2015, and interpolate for the years that match our annual sample in 1988–2015. However, the USGS data is only available for relatively aggregated categories, such as livestock, irrigation, etc, so we disaggregate the USGS categories based
Figure A1. Year-by-year estimates pooling all states and all industries. Note: Coefficients plotted are for the triple interaction terms of the US water intensity measure, the MDB states indicator, and yearly dummies. The benchmark year is 1988. Control variables are consistent with Column (1) of appendix table 2.

Appendix Table 2. The effect of water market reforms on state-level export shares (MDB vs non-MDB).

| Variables | IV: US water intensity | OLS results |
|-----------|------------------------|-------------|
|           | (1)                    | (2)         | (3) | (4) |
| Period (94–06) × MDB | −0.058 | −0.089 | −0.049** | −0.046* |
| × Water intensity | (0.110) | (0.105) | (0.020) | (0.022) |
| Period (07–15) × MDB | −0.047 | −0.098 | 0.074** | 0.058 |
| × Water intensity | (0.094) | (0.113) | (0.015) | (0.070) |
| Period (94–06) × MDB × Drought | — | −0.359*** | — | −0.113** |
| × Water intensity | — | (0.101) | — | (0.041) |
| Period (07–15) × MDB × Drought | — | −0.423 | — | −0.103 |
| × Water intensity | — | (0.362) | — | (0.109) |
| Industry-year control variables | Yes | Yes | Yes | Yes |
| State × industry FE | Yes | Yes | Yes | Yes |
| State × year FE | Yes | Yes | Yes | Yes |
| Other interactions terms | Yes | Yes | Yes | Yes |
| Observations | 3753 | 3753 | 3753 | 3753 |
| Number of state × industry | 137 | 137 | 137 | 137 |

Note: a ‘Period (94–06)’ and ‘Period (07–15)’ are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period); ‘MDB’ is the 1,0 indicator for MDB states; ‘Water intensity’ in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

b ‘Drought’ is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.

c ‘Industry-year control variables’ includes water intensity and the logarithmic values of world total import (except Australia).

d ‘Other interaction terms’ include ‘MDB × Water intensity’, ‘Period (94–06) × Water intensity’, and ‘Period (07–15) × Water intensity’ for Columns (1) and (3), and Columns (2) and (4) additionally include ‘Period (94–06) × Drought × Water intensity’, ‘Period (07–15) × Drought × Water intensity’, ‘Drought × Water intensity’, and ‘Drought × MDB × Water intensity’.

e Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses, ** ** p < 0.01, ** p < 0.05, * p < 0.1.

on Blackhurst et al (2010), which estimate a detailed Input–Output Vector of 2002 Water Withdrawals for the United States in the supplemental materials. Using this 2002 measure of water withdrawals as the reference, the water productivity for other years in our sample period is assumed to evolve following the changes in labor productivity over the corresponding period. The labor productivity measure comes from
Appendix Table 3. The effect of water market reforms on agricultural export shares (MDB vs non-MDB).

| Variables | IV: US water intensity | OLS results |
|-----------|------------------------|-------------|
|           | (1)                    | (2)         | (3)         | (4)         |
| Period (94–06) × MDB | 0.581** | 0.438 | 0.037*** | 0.045*** |
| × Water intensity$^a$ | (0.255) | (0.286) | (0.010) | (0.010) |
| Period (07–15) × MDB | 0.104 | 0.016 | −0.004 | −0.001 |
| × Water intensity$^a$ | (0.527) | (0.790) | (0.204) | (0.220) |
| Period (94–06) × MDB × Drought$^b$ | − | −1.17** | − | −0.077*** |
| × Water intensity$^a$ | − | (0.541) | − | (0.021) |
| Period (07–15) × MDB × Drought$^b$ | − | −1.48* | − | −0.048 |
| × Water intensity$^a$ | − | (0.872) | − | (0.053) |
| Industry-year control variables$^c$ | Yes | Yes | Yes | Yes |
| State × industry FE | Yes | Yes | Yes | Yes |
| State × year FE | Yes | Yes | Yes | Yes |
| Other interactions terms$^d$ | Yes | Yes | Yes | Yes |
| Observations | 2185 | 2185 | 2185 | 2185 |
| Number of state × industry | 81 | 81 | 81 | 81 |

Note: $^a$ Period (94–06) and Period (07–15) are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period); 'MDB' is the 1,0 indicator for MDB states; 'Water intensity' in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

$^b$ 'Drought' is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.

$^c$ Industry-year control variables' includes water intensity and the logarithmic value of world total import (except Australia).

$^d$ Other interaction terms’ include ‘MDB × Water intensity’, ‘Period (94–06) × Water intensity’, and ‘Period (07–15) × Water intensity’ for Columns (1) and (3), and Columns (2) and (4) additionally include ‘Period (94–06) × Drought × Water intensity’, ‘Period (07–15) × Drought × Water intensity’, ‘Drought × Water intensity’, and ‘Drought × MDB × Water intensity’.

** Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses, ***, p < 0.01, ** p < 0.05, * p < 0.1.

Appendix Table 4. The effect of water market reforms on state-level export shares in MDB states.

(Adding state-year fixed effects)

| Variables | IV: US water intensity | OLS results |
|-----------|------------------------|-------------|
|           | (1)                    | (2)         | (3)         | (4)         |
| Period (94–06) | −0.146 | −0.118 | −0.056** | −0.049* |
| × Water intensity$^a$ | (0.091) | (0.091) | (0.016) | (0.017) |
| Period (07–15) | −0.188*** | −0.091*** | −0.012 | 0.026 |
| × Water intensity$^a$ | (0.069) | (0.014) | (0.025) | (0.026) |
| Period (94–06) × Drought$^b$ | − | −0.467*** | − | −0.076** |
| × Water intensity$^a$ | − | (0.051) | − | (0.021) |
| Period (07–15) × Drought$^b$ | − | −0.847*** | − | −0.241** |
| × Water intensity$^a$ | − | (0.145) | − | (0.044) |
| Industry-year control variables$^c$ | Yes | Yes | Yes | Yes |
| State × year FE | Yes | Yes | Yes | Yes |
| State × industry FE | Yes | Yes | Yes | Yes |
| Observations | 1844 | 1844 | 1844 | 1844 |
| Number of state × industry | 68 | 68 | 68 | 68 |

Note: $^a$ Period (94–06) and Period (07–15) are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period); 'Water intensity' in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

$^b$ ‘Drought’ is 1 if the total precipitation in is part of the lower 25th percentile of the state’s precipitation over the entire 20th century, and 0 otherwise.

$^c$ Industry-year control variables' includes water intensity and the logarithmic values of world total import (except Australia).

$^d$ Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses, ***, p < 0.01, ** p < 0.05, * p < 0.1.

the US Labor Productivity, Division of Industry Productivity Studies published by the Division of Industry Productivity Studies in the Office of Productivity and Technology at the Bureau of Labor Statistics in published in 20 July 2017.

The denominator for the output value by industry also comes from the same publication provided by the Bureau of Labor Statistics in 2017 that is mentioned above, which consistently provides the necessary statistics for our entire sample period.

After putting all the above parameters into equation (A2), we are able to construct a water intensity measure for the US industries covering our entire sample period.
Appendix Table 5. The effect of water market reforms on state-level export shares (MDB vs non-MDB).

(Using MDB-year fixed effects instead of state-year fixed effects)

| Variables | IV: US water intensity | OLS results |
|-----------|------------------------|-------------|
|           | (1)                    | (2)         | (3) | (4) |
| Period (94–06) × MDB | −0.059 | −0.089 | −0.049** | −0.048* |
| ×Water intensityc | (0.110) | (0.105) | (0.019) | (0.021) |
| Period (07–15) × MDB | −0.048 | −0.099 | 0.074*** | 0.063 |
| ×Water intensityc | (0.093) | (0.113) | (0.014) | (0.054) |
| Period (94–06) × MDB × Droughtb | — | −0.359*** | — | −0.079** |
| ×Water intensityc | — | (0.101) | — | (0.029) |
| Period (07–15) × MDB × Droughtb | — | −0.423 | — | −0.078 |
| ×Water intensityc | — | (0.362) | — | (0.083) |
| Industry-year control variablesc | Yes | Yes | Yes | Yes |
| State-year control variablesd | Yes | Yes | Yes | Yes |
| State × industry FE | Yes | Yes | Yes | Yes |
| MDB × year FE | Yes | Yes | Yes | Yes |
| Other interactions termsc | Yes | Yes | Yes | Yes |
| Observations | 3753 | 3753 | 3753 | 3753 |
| Number of state × industry | 137 | 137 | 137 | 137 |

Note:  

1. Period (94–06) and Period (07–15) are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period); 'Water intensity' in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

2. Drought is 1 if the total precipitation in is part of the lower 25th percentile of the state's precipitation over the entire 20th century, and 0 otherwise.

3. 'Industry-year control variables' includes water intensity and the logarithmic values of world total import (except Australia).

4. 'State-year control variables' include export share of mining, logarithmic values of employment and capital stock, the drought dummy, and weather controls for the current and previous years including precipitation, HDDs above 8°C and above 32°C, respectively.

5. 'Other interaction terms' include 'Period (94–06) × Drought' and 'Period (07–15) × Drought' for Columns (1) and (3), and Columns (2) and (4) additionally include 'Period (94–06) × Drought × Water intensity', 'Period (07–15) × Drought × Water intensity', 'Drought × Water intensity', and 'Drought × MDB × Water intensity'.

*Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses, ** p < 0.01, *** p < 0.05, * p < 0.1.

Appendix Table 6. The effect of water market reforms on state-level export shares in MDB states.

(Controlling domestic demand by industry categories)

| Variables | IV: US water intensity | OLS results |
|-----------|------------------------|-------------|
|           | (1)                    | (2)         | (3) | (4) |
| Period (94–06) | −0.128* | −0.086 | −0.072* | −0.021 |
| ×Water intensityc | (0.069) | (0.081) | (0.023) | (0.020) |
| Period (07–15) | −0.040 | 0.076 | −0.120 | 0.144 |
| ×Water intensityc | (0.053) | (0.098) | (0.090) | (0.091) |
| Period (94–06) × Droughtb | — | −0.504*** | — | −0.106** |
| ×Water intensityc | — | (0.066) | — | (0.029) |
| Period (07–15) × Droughtb | — | −0.868*** | — | −0.251*** |
| ×Water intensityc | — | (0.135) | — | (0.030) |
| Industry-year control variablesc | Yes | Yes | Yes | Yes |
| State-year control variablesd | Yes | Yes | Yes | Yes |
| State × industry and year-FE's | Yes | Yes | Yes | Yes |
| Other interactions termsc | Yes | Yes | Yes | Yes |
| Observations | 1844 | 1844 | 1844 | 1844 |
| Number of state × industry | 68 | 68 | 68 | 68 |

Note:  

1. Period (94–06) and Period (07–15) are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period); 'Water intensity' in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

2. Drought is 1 if the total precipitation in is part of the lower 25th percentile of the state's precipitation over the entire 20th century, and 0 otherwise.

3. 'Industry-year control variables' includes water intensity, the logarithmic value of world total import (except Australia), and domestic demand by industry categories with data extrapolated for 1988–94.

4. 'State-year control variables' include export share of mining, logarithmic values of employment and capital stock, the drought dummy, and weather controls for the current and previous years including precipitation, HDDs above 8°C and above 32°C, respectively.

5. 'Other interaction terms' include 'Period (94–06) × Drought' and 'Period (07–15) × Drought' for Columns (2) and (4).

*Weighted by the average total annual export by states in pre-reform years. Standard errors clustered by states in parentheses, ** p < 0.01, *** p < 0.05, * p < 0.1.
Appendix Table 7. The effect of water market reforms on state-level export shares (MDB vs non-MDB).

| Variables | IV: US water intensity | OLS results |
|-----------|------------------------|-------------|
|           | (1)                    | (2)         | (3) | (4) |
| Period (94–06) × MDB | −0.063                 | −0.093      | −0.056** | −0.052* |
| × Water intensity\(a\) | (0.109)                | (0.105)     | (0.023) | (0.024) |
| Period (07–15) × MDB | −0.051                 | −0.100      | 0.066** | 0.054 |
| × Water intensity\(a\) | (0.094)                | (0.115)     | (0.018) | (0.074) |
| Period (94–06) × MDB × Drought\(b\) | —                   | −0.358*** | —      | −0.115** |
| × Water intensity\(b\) | (0.102)                | (0.102)     | (0.047) |         |
| Period (07–15) × MDB × Drought\(b\) | —                   | −0.430      | —      | −0.119 |
| × Water intensity\(b\) | (0.366)                | (0.366)     | (0.110) |         |
| Industry-year control variables\(c\) | Yes                   | Yes         | Yes   | Yes |
| State × industry FE | Yes                   | Yes         | Yes   | Yes |
| State × year FE | Yes                   | Yes         | Yes   | Yes |
| Other interactions terms\(d\) | Yes                   | Yes         | Yes   | Yes |
| Observations | 3753                  | 3753        | 3753  | 3753 |
| Number of state × industry | 137                   | 137         | 137   | 137 |

Note: \(a\) 'Period (94–06)' and 'Period (07–15)' are 0/1 indicators for 1994–2006 and 2007–15, respectively (1988–93 serves as the baseline period); \(b\) 'MDB' is the 1,0 indicator for MDB states; 'Water intensity' in 100 l per Australian dollar varies by the three periods (i.e. 1988–93, 1994–2006, 2007–15).

Alternative, in Columns (1) and (2), we can econometrically shut off this endogenous response of water use technology/techniques to identify the pure compositional effects of water market reforms by employing the corresponding US water intensity measures as IV. This IV approach is also called 2SLSs where the endogenous variables (water intensity measure of Australia and its interaction terms) and the outcome variable (export composition) are estimated in two consequent stages. In the first stage regressions, each one of the interaction terms of Australia's water intensity measure and the water intensity itself are regressed on the corresponding US measures, as well as all other control variables. In the second stage regressions, the predicted values of the first-stage outcomes are incorporated (instead of the raw Australian water intensity terms) to estimate their effects on export composition. The latter boils down to assuming the Australian water intensity measures follows the corresponding US industries over time without any endogenous responses to Australia's water market reforms.

Appendix Table 7. The effect of water market reforms on state-level export shares (MDB vs non-MDB).
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