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More market, more efficiency? Water market impacts on water use efficiency in the Australian agricultural sector

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Abstract

Water markets emerged as economic tools to deal with water scarcity. By reallocating existing water resources instead of using costly engineering projects to extend the existing supply, they are expected to increase the efficiency of water resources allocation. In this article we question empirically the impacts of water markets on the efficiency of agricultural production, as defined by a stochastic frontier approach. Using regional data on agricultural production and climatic factors, we analyze the link between the existence of water markets, the intensity of water trade and the efficiency of agricultural production in Australia, home to some of the most developed water markets in the world. We find that the existence of water markets in a region is associated with higher agricultural production efficiency, but no significant relationship is identified between the intensity of water trade and efficiency.

Keywords: water markets; stochastic frontier; technical efficiency in agricultural production; Murray-Darling Basin

JEL classification: Q56; Q25; Q15

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Introduction

Water markets have emerged as potential tools to manage water under scarcity conditions. Such markets can be defined as systems of rules and regulations that govern the buying, selling and leasing of water use rights (Debaere et al. 2014). They can be used within the agricultural sector; or they can allow inter-sectoral trades, as in the case of rural to urban transfers. Although water markets can be used to improve irrigation water quality (Weinberg, Kling and Wilen 1993) and environmental outcomes (Grafton and Horne 2014), the main justification for the use of market mechanisms applied to water resources is that they are expected to increase the overall efficiency of water use. Two forms of water use efficiency are considered in this article. Allocative efficiency refers to water being allocated to where it generates the most income, while technical efficiency refers to improvements in the efficient use for water through technology (Wheeler, Zuo and Hughes 2014). Water markets can foster allocative efficiency gains (Griffin and Hsu 1993) by redirecting water from low-valued to higher valued uses (Dinar, Rosegrant and Meizen-Dick 1997), and towards more productive activities (Hodgson 2006). They can also increase technical efficiency through the expansion of water use by highly efficient new water users, adoption of water conserving technologies and elimination of inefficient uses for water (Qureshi, Shi and Proctor 2009).

Water markets have been established in various parts of the world. Examples of formal (i.e. regulated and designed by a central authority) water markets include Australia (Grafton, Horne and Wheeler 2016), the western United States (Colby 1990), Chile (Bitran, Rivera and Villena 2014), Spain (Palomo-Hierro, Gómez-Limón and Riesgo 2015) and China (Zhang 2007). Examples of informal (i.e. transactions happening under limited or no scrutiny from the central authority) water markets can be found in India (Mukherji 2007) or Pakistan (Razzaq et al. 2019). Recently, the use of water markets in other contexts has been considered, in order to face the challenges induced by water scarcity (Mellah 2018; Wheeler et al. 2017). As water markets showed a low social acceptability in many contexts as France (Figureau, Montginoul and Rinaudo 2015) or Italy (Zavalloni, Raggi and Viaggi 2014), informing the debate on their empirical effects in the context of existing water markets is important.

Australia is a good case study for the use of water markets and economic tools in a context of water scarcity. For the most part of its territory, Australia is facing significant physical water scarcity (UN 2012), as water resources development is approaching or has already exceeded sustainable limits. The first water markets in Australia were established in the early 1980s. Since then, water markets developed through progressive reforms while trading volumes and irrigators' participation in water markets have consistently increased through time (Wheeler, Zuo and Hughes 2014) and water markets in the Murray-Darling Basin have been described as some of the most advanced water markets in the world (Grafton et al. 2011).

Different studies have attempted to demonstrate the economic benefits of water markets in Australia, using a general equilibrium approach (Peterson et al. 2005; NWC 2012) or analyzing market bid and ask transactions at the micro-economic level (Brooks and Harris 2008). However, no empirical study has considered the impacts of Australian water markets on water use efficiency in practice. This study contributes to the empirical literature focusing on water markets' economic impacts by analyzing the relationship between water markets and the efficiency of water use in Australia. To do so, we used a stochastic frontier approach and agricultural, climatic and market data between 2011 and 2017. Results from this study can be used to inform the debates related to water markets performance in the Australian context and to their potential adoption in other contexts.

Literature review: water markets, expected benefits and impacts on water allocation efficiency

Markets emerged in the early literature as a feasible alternative to central water management, described as limited in its ability to reallocate resources efficiently. In this perspective, it focuses on the benefits expected from water transfers.

Different studies dedicated to water market impacts simulate their existence to estimate potential benefits. Vaux and Howitt (1984) considered the possibility of interregional water transfers in California. Using a general equilibrium approach, the authors compared the costs of such transfers to those of a gradual supply extension in water's area of arrival to meet the expected demand. The net benefits estimated from the transactions for buyers and sellers amount to USD$66 million for the year 1980, and are expected to increase to USD$220 million for the year 2020. Dinar and Letey (1991) estimate profit functions for farmers in the San Joaquin Valley and consider the ability to trade water. Their results show better abilities to invest in irrigation technology, decreased environmental pollution and a potential reallocation of water towards the urban sector. Whittlesey and Willis (1998) analyze different alternatives aimed at maintaining a minimum flow in the Walla Walla River Basin (State of Washington, USA). Using a model predicting agricultural behavior and stream flows in the basin, they find markets as the most cost-effective approach. In Australia, Peterson et al. (2005) use general equilibrium modelling to introduce the ability to trade water in the Australian economy. Their results indicate important gains in Regional Domestic Product where water is traded with a positive global impact on Australia's GDP. This impact is described as particularly important in years of drought (AUD$555 million in a year subjected to important water scarcity, and AUD$201 million in a year subject to a relative abundancy), suggesting water markets might alleviate the economic effect of droughts on the Australian economy.

Another section of the empirical literature attempting to measure water market's economic impacts analyzes actual transaction data at a microeconomic level. Hearne and Easter (1997) analyzed transactions from water markets in Chile in the agricultural sector. They compared water values determined by crop budget to prices included in water trades. They found gains from trade varying from $1000 per share to $10 000 per share, depending on the time and location of trades. In Australia, Bjornlund (1999) focused on transactions in two specific areas of the Murray-Darling Basin and related them to the characteristics of the irrigators involved. He found that water was in average moving towards more efficient buyers that were also growing higher-valued crops. Brooks and Harris (2008) analyze data from three trading zones in northern Victoria to determine consumer and producer surplus. They find surpluses of $20 000 a week in the Greater Goulburn area.

Besides gains from trade, different empirical studies showed that water markets are used by irrigators to improve their risk management. Farmers tend to be risk averse, under different modalities (Nauges, Wheeler and Zuo 2015); water markets can provide a reliable source of water in times of needs or an additional source of income, thereby positively affecting farm budgets (Wheeler, Zuo and Hughes 2014). This has been shown empirically in Australia, particularly in the horticultural sector as permanent trees and vines could die if they are exposed to excessive water stress (Loch et al. 2012). Besides, farmers experiencing a high variability in profits have incentives to trade more on water markets (Cristi 2007; Calatrava and Garrido 2005). Therefore, water markets are expected to improve farmer's ability to manage their water related risks (Zuo, Nauges and Wheeler 2015).

In parallel to these benefits, limits to the use of water markets that could prevent them to improve efficiency in the use of water resources have been widely commented, often in a context of limited market development. Classical limits to the use of markets are often amplified in the case of water: as water is a massive resource, the costs raising from moving the resource can be high (Turner et al. 2004). Some of the transaction costs related to water trading are analyzed by Colby (1990) in the western United States, who concludes that the administrative costs are not to be considered as 'overly burdensome' to transactions in the western United States water markets around 1990. Moreover, there is a potential for third party effects (Bourgeon, Easter and Smith 2008). Changes in streamflows, return flows and impacts on water's area of origin are frequently cited in that matter and can mitigate the gains obtained by buyers and sellers (Garrido Fernández 2016). Furthermore, an externality often described by the literature is the 'stranded asset' problem (Chong and Sunding 2006; Heaney et al. 2006; Bjornlund 2008; Frontier Economics et al. 2007): as irrigation water use requires heavy investment in infrastructures, these infrastructures are often shared by different users. If one of these users decides to sell his or her water entitlement, the maintenance costs of the infrastructure will be supported by the remaining users, who generally compete with the leaver. When an irrigator sells his rights permanently, the lack of maintaining work on his property can bring weeds and increase disease risk for the neighbors (Frontier Economics et al. 2007; Bjornlund 2008) or even cause soil erosion (Chong and Sunding 2006). In this perspective, a range of institutions and reforms have been identified as necessary to foster water market benefits (Wheeler et al. 2017). As an example, the use of security-differenciated water rights has been suggested to improve market performance (Lefebvre, Gangadharan and Thoyer 2012).

Our article makes several interesting contributions. Firstly, it questions the ability of water markets to enhance water use efficiency. We apply a panel data stochastic frontier model to regional Australian data on agricultural production, climatic factors, and market variables in order to analyze the relationship between water markets and efficiency of water use. We also show the usefulness of our model by proposing a short-term prediction exercise. Indeed, our model can be interestingly employed to assess the efficiency of current water use as it can help distinguishing regions which optimally consume water from regions which sub-optimally consume (i.e. under- or over-use) water during their current production. This exercise allows us to make recommendations for these inefficient regions to revise (i.e. increase or reduce) their water consumption in order to improve their production efficiency.

Research hypotheses

In the Australian case, Bjornlund (1999) studies two specific areas presenting water markets in the Murray-Darling Basin. He noticed that water was sold to more efficient farmers in terms of water use and value generated. In a similar perspective, Wheeler, Zuo and Hughes (2014) reported that in the decade preceding 2014, water has been sold from annual crops (rice, cotton, mixed farming) to horticultural crops, due to a more inelastic demand from vegetables and perennial horticultural activities. These transactions implied a higher value-added use per unit of water, considering marginal contribution of irrigation water to profit of $547/ML and $61/ML, for horticulture and broadacre crops respectively (Nauges, Wheeler and Zuo 2015). Generalizing these arguments at the regional level, we expect water market transactions from lower-valued uses towards higher valued uses to increase the allocative efficiency overall. Furthermore, we expect water markets to generate incentives from higher technical efficiency users to buy water from lower technical efficiency users (Qureshi, Shi and Proctor 2009). Thus, we formulate our first research hypothesis:

H1: In regions where water markets have been established, water use efficiency (i.e. as measured by the output value generated by one unit of water) of agricultural water use is greater.

Water markets have developed in different scales throughout Australia. As described in figure 1, the MDB represents about 85% of all water market transactions in Australia. This is related to the fact that the southern MDB represented a large hydrologically connected area, unlike other parts of Australia, thus involving more potential users (Wheeler, Zuo and Hughes 2014). Besides, more active water markets imply an increased access to market infrastructure and information. Therefore, we expect more active water markets such as markets within the southern MDB to facilitate water use efficiency enhancement:

H2: In regions where more active water markets are in place (i.e. more transactions occur), water use efficiency should be higher.

This article therefore questions the impact of water markets existence (H1) and intensity (H2) on water use efficiency between 2011-12 and 2016-17 in Australia. To do so, we use a stochastic frontier model at a regional level, and Australian data on market existence and intensity, agricultural production, inputs, and climatic circumstances.

Background: Agriculture and water markets in Australia

In the last decades, agriculture in Australia has been evolving under the impact of the Millenium Drought, that occurred between 2002-03 and 2010-11. Our period of study begins in 2011-12, in a relatively wet year marking the end of the Millenium Drought. Between 2011-12 and 2017-18, the total Australian agricultural production value increased from 45.5 to 51.3 billion AUD$:

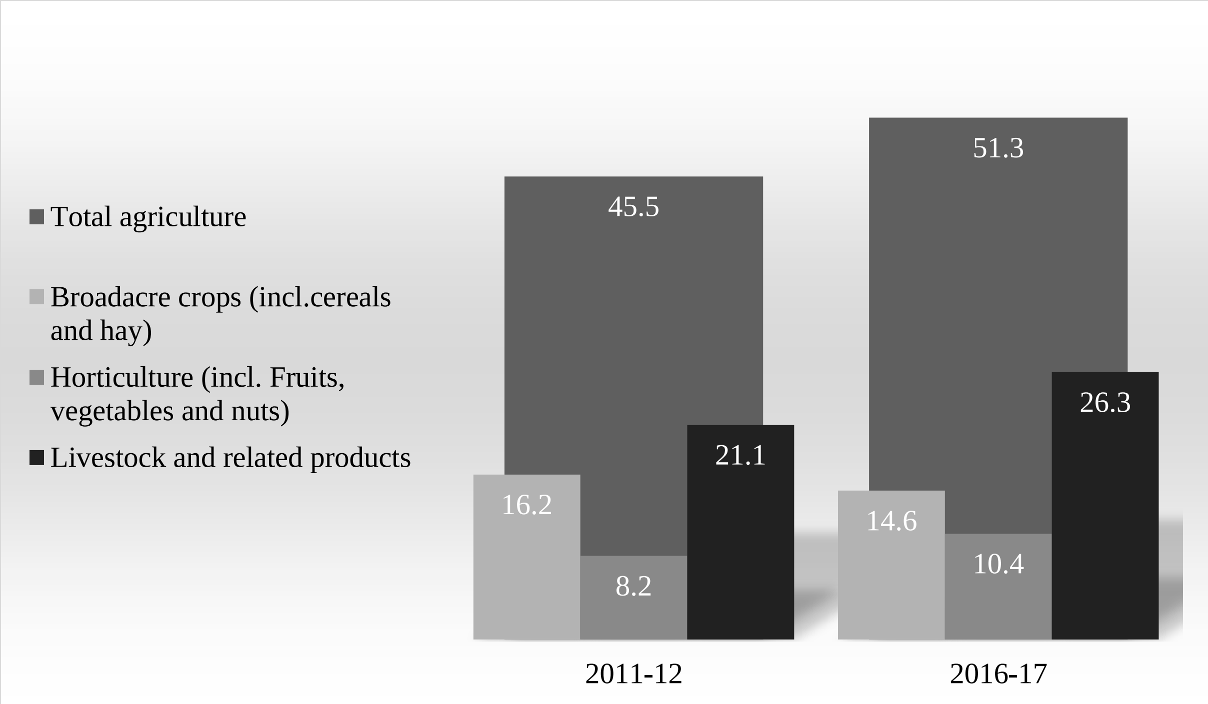

Figure 1. Total agricultural production value in Australia, overall and by category, 2011-12 and 2016-17. Source: Data from the Australian Bureau of Statistics (2013; 2018). Figures are in billion $AUD, corrected for inflation using constant 2011 prices.

The overall 11% increase in total production value is related to a strong development of horticulture (the fruits and nuts industry in particular) and livestock, in spite of a decline the production value associated with broadacre crops. In particular, cereal production value dropped by about 15% (ABS 2013; 2018). Thus, over our period of study, a decline in lower-valued crops (as cereals) and a development of higher valued crops (fruits and nuts, vegetables) can be noted.

Water trade is, for logistical and juridical reasons, only possible between hydrologically connected zones. As a consequence, there is not one national water market in Australia but many trading zones based on hydrological connectivity. There are two types of market transactions ongoing in the Australian water markets. Entitlement trading implies the exchange of ongoing rights to exclusive access to a share of water otherwise known as permanent water. Water allocations trading involves the exchange of a specific volume of water allocated to water entitlements in a given season otherwise known as temporary water (Haensch, Wheeler and Zuo 2019). Figure 2 shows that during the fiscal year 2016-17, approximately 7500 GL were traded in Australian water markets, representing a global turnover of AUD$131 million (ABARES 2018).

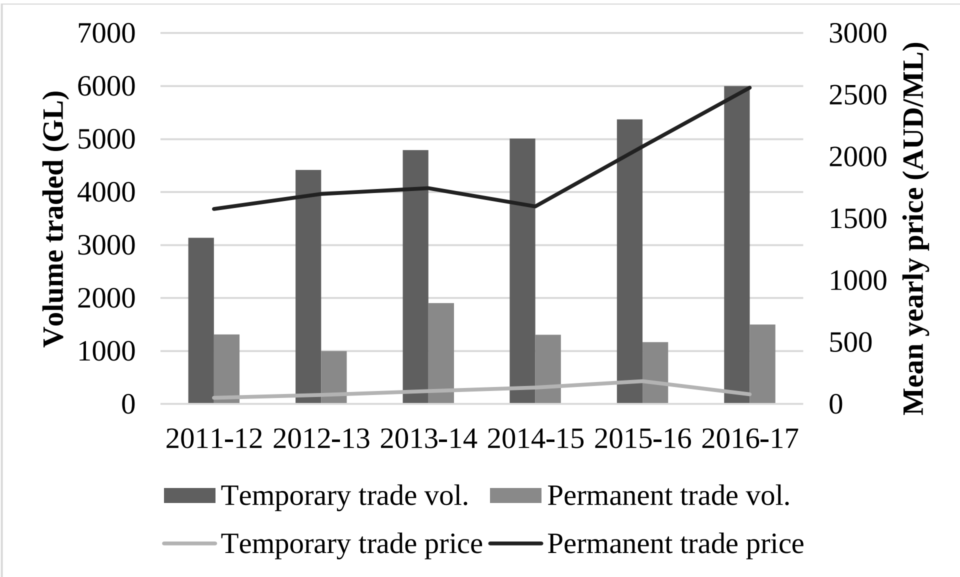

Figure 2. Temporary and permanent water trading prices and volumes in Australia, 2011-12 to 2016-17. Source: Data in ABARES (2018)

Between 2011-12 and 2016-17, the volume of temporary water rights traded (allocations) has consistently increased, while allocation prices fluctuated depending on climatic circumstances. Besides, although the volume of permanent water rights traded remained globally stable, the price of permanent water rights also increased, under the joint influence of water scarcity and federal environmental water buyback programs.

Australian water markets historically involved irrigators as the most important actors of water trade. Other actors involved in the process of exchanging water rights in Australia include water brokers who provide market information and trading platforms to irrigators, federal and national authorities who launched an important buyback program destined to restitute water to the environment, and Irrigation Infrastructure Operators (IIOs) who typically own blocks of water rights on behalf of irrigators, and redistribute these rights to their members. These actors trade under federal, national and sometimes local regulations that have been progressively adapted to increase irrigators' participation to water markets.

The process historically establishing Australian water markets implied different steps. Australian water markets were historically created around the agricultural sector in the Murray-Darling Basin (MDB) (Maziotis, Calliari and Mysiak 2013) and it is where water trade is the most developed and established, as illustrated by figure 3.

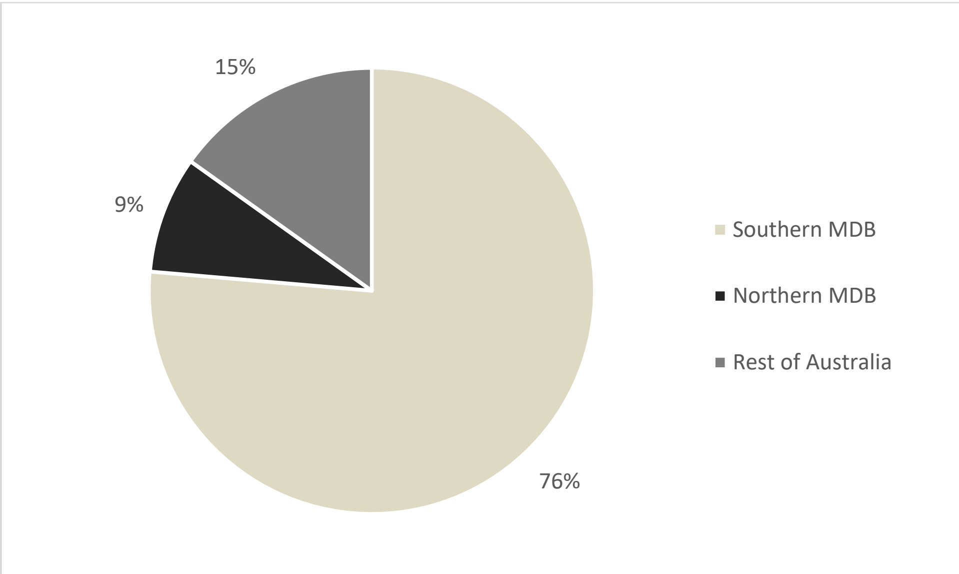

Figure 3. Proportion of Australian water trades (temporary and permanent) occurring within and outside the Murray-Darling Basin, 2016-17. Source: Data in ABARES (2018)

The basin involves parts of four Australian States: New South Wales, Victoria, Queensland, and South Australia. It also includes the Australian Capital Territory. As the MDB is subject to a climate favoring irrigated agriculture in comparison with the semi-arid climate found northwards, agriculture covers 67% of its territory and represents about 40% of the total Australian agricultural production. Nonetheless, the basin is subject to significant water scarcity issues strongly affecting actors involved in the farming industry (Daghagh Yazd, Wheeler and Zuo 2020). This and the prevalence of irrigated agriculture contribute to explain the emergence of water markets in the area, as market for water resources potentially appears when water demand approaches water availability (Debaere et al. 2014). The important volume of water trade and the institutional framework fostering water markets in the southern MDB led Grafton et al. (2011) to describe water markets in the Murray-Darling Basin as the most advanced in the world.

In 1994, a cap was established on total water extraction in the Murray-Darling Basin. This decision set the maximum level of water extraction in the basin at the 1994 extraction level. This step caused a large increase in the water traded on the market, as additional needs for water had to be fulfilled through the market. In 2004, the National Water Initiative (NWI) precisely defined the generic terms ‘entitlement’ and ‘allocation’, common to all Australian States, in an effort to unify the existence of many different water markets. It recognized the need for better designed water markets to improve efficiency in water uses, in a context of low participation to such markets. In 2007, the national ‘Water Act’ took additional steps to decrease barriers to trade. In 2012, the Murray-Darling Basin Plan defined freedom of trade as the norm and restrictions to trade in the Basin as exceptions, while establishing an authority in the Basin responsible for the management of water resources. Towards the end of the Millenium drought, the Australian Federal government dedicated AUD$3.1 billion to buy water rights from about 4500 willing irrigators in order to increase environmental flows in the

MDB (Wheeler and Cheeseman, 2013). Furthermore, the SRWUI program planned an additional AUD$5.8 billion for water-related investments (Haensch, Wheeler and Zuo 2019). While the 'buyback' program reduced the overall water use in some areas within the Murray-Darling Basin (Department of Land, Water and Environment 2018), investments aiming to develop on-farm water use efficiency (Haensch, Wheeler and Zuo 2019) have been widely criticized by economists for various reasons, including higher costs (Qureshi et al. 2011) and a lack of accounting for return flows (Williams and Grafton 2019) that could eventually increase consumptive use at the expense of environmental flows (Loch and Adamson 2015).

Data

The data analyzed in the next sections was obtained through different sources than can be found in Appendix A, along with descriptive statistics. The analysis was conducted on 54 Australian Natural Resource Management Regions, as defined by the ABS, between the fiscal years 2011-12 and 2016-17.

Agricultural data on water use and total agricultural area was extracted from the Australian Bureau of Statistics (ABS). For each year from 2011-12 to 2016-17 we collected information on 'Value of Agricultural Commodities Produced' and 'Water Use on Australian Farms'. Moreover, as climate has been described as the most important determinant of agricultural productivity, mainly through its influence on temperature and water regimes (Kang, Khan and Ma 2009), we included rainfall and potential evapotranspiration to the analysis. Such variables were sourced from the Australian Bureau of Meteorology. As estimates of rainfall or temperature at the NRM region level were not available, the data has been computed based on the rainfall, latitude and temperature of 5 (temperature) to 10 individual stations across each natural resource management region in Australia. In particular, the mean monthly temperature was defined based on the mean maximum temperature (defined as the average of daily maximum temperatures in a given month) and the mean minimum temperature (the average of daily minimum temperatures in a given month), following Allen et al. (1998):

$$Mean\,Temperature = \frac{Mean\,Max\,Temperature + Mean\,Min\,Temperature}{2}$$

As potential evapotranspiration (PE) is often described as a better predictor than temperature and is widely used in the literature (see Webb 2006 or Blanc, Lepine and Strobl 2016 for examples), we computed the mean monthly PE based on the FAO Penman-Monteith equation, as recommended by Allen et al. (1998). Some missing climatic data (wind speed, radiations, etc.) was simulated according to Allen et al.'s advice.

Finally, two market variables were defined at the region level, based on our two research hypotheses. First, the existence of a functioning water market in region i (i.e the occurrence of at least one recorded transaction in the past) was coded through a binary variable. Second, we used the volume of additional water bought through water markets in each region as a proxy for water trade intensity.

Econometric framework

A panel data stochastic frontier model

This section presents the stochastic production frontier model applied to our data. Widely used in the literature dedicated to the analysis of technical efficiency in agriculture (see, e.g., Nguyen-Van and To-The 2016), such frontiers have been previously applied to the Australian grape production by Hughes (2011) or Coelli and Sanders (2012). Specifically, we use the inefficiency frontier model for panel data presented by Battese and Coelli (1995).

We assume that output y_{it} of farmer $i, i = 1,2, \ldots, n$ at time t, $t = 1,2, \ldots, T$ is subject to random shocks v_{it} and a degree of efficiency $\omega_{it} \in (0,1]$:

$$y_i = f(x_{it};\ \beta)\omega_{it} \exp(v_{it}),\ \ i = 1,2, \ldots, n, \tag{1}$$

where x_i is a Kx1 vector of inputs, β a Kx1 vector of parameters to be estimated.

By assuming $\omega_{it} = \exp(-u_{it})\ \ with\, u_{it} \geq 0$, we obtain

$$y_i = f(x_{it};\ \beta) \exp(v_{it} - u_{it})\, , i = 1,2, \ldots, n, \tag{2}$$

Note that v_{it} corresponds to the usual error term capturing random variation in output due to factors beyond the control of producers and is assumed to be independent and identically distributed $N(0, \sigma_v^2)$. Inefficiency is captured in u_{it} which is assumed to be independent and identically distributed non-negative truncations of the $N(\mu, \sigma_u^2)$ distribution. The condition $u_{it} \geq 0$ ensures that all observations lie on or beneath the production frontier.

Applying log transformation to equation (2) we get

$$lny_{it} = lnf(x_{it};\ \beta) + v_{it} - u_{it} \tag{3}$$

Note that, following Battese and Coelli (1995), we can specify a conditional mean model for u_{it} as $\mu = z_{it}\delta$, or equivalently

$$u_{it} =\ z_{it}\delta + \varepsilon_{it} \tag{4}$$

where z_{it} is a Jx1 vector of explanatory variables. This vector includes the existence or intensity of water markets in the considered NRM region and climatic variables (potential evapotranspiration and Rainfall) and year dummies. ε_{it} is defined by the truncation of the normal distribution with zero mean and variance σ^2, such that $\varepsilon_{it} \geq -z_{it}\delta$ (see Battese and Coelli 1995 for details).

We simultaneously estimate the inefficiency u_{it} and a conditional mean model for u_{it} using a vector of explanatory variables in order to analyze their respective impacts on inefficiency. Note that we are especially interested in the sign of our market variable's parameter in this regard.

In this model, the efficiency of a given region i at time t is defined as the ratio of its production to its corresponding production if the region used its inputs in a perfectly efficient way. An estimation for efficiency $\omega_{it} = \exp(-u_{it})$ can be given by (see Battese and Coelli 1993 for panel data, or Jondraw et al. 1982 for cross-sectional data):

$$TE_{it} = E\{\exp(-u_{it})\,|v_{it} - u_{it}\} = \left\{\frac{\Phi\left[\left(\frac{\mu_*}{\sigma_*}\right) - \sigma_*\right]}{\Phi\left(\frac{\mu_*}{\sigma_*}\right)}\right\} \exp\left[-\mu_* + \frac{1}{2}{\sigma_*}^2\right] ,$$

where: $\mu_* = \frac{\left[\, z\delta\sigma_v^2 - (v_{it} - u_{it})\sigma^2\,\right]}{\sigma_v^2 + \sigma^2}$, $\sigma^{*2} = \frac{\sigma^2{}_v\sigma^2}{{\sigma_v}^2 + \sigma^2}$, and $\Phi(.)$ is the distribution function of the standard normal distribution.

In order to compute the technical efficiency scores, we need to estimate the parameters from the equations (3) and (4). This can be performed by Maximum Likelihood (See Battese and Coelli 1993 for a detailed equation of this model's log-likelihood). However, in order to estimate the vector of parameters β, we have to specify the f function. As described with our data, we consider 2 inputs in the production function (agricultural area and water use) and a range of control variables including climatic variables (rainfall, temperature, potential evapotranspiration) and other variables (existence of a water market, location within the Murray-Darling Basin…).

Two different specification strategies were tested in this article. We consider a Cobb-Douglas function, i.e.:

$$\ln f(x_{it}, \beta) = \beta_0 + \beta_1 \ln AREA_{it} + \beta_2 \ln Wateruse_{it},$$

and a more general function (translog), i.e.:

$$\ln f(x_{it}, \beta) = \beta_0 + \beta_1 \ln AREA_{it} + \beta_2 \ln Wateruse_{it}$$
$$+ \beta_3 (\ln AREA_{it})^2 + \beta_4 (\ln Wateruse_{it})^2 + \beta_5 \ln AREA_{it} \ln Wateruse_{it}$$

Akaike and Schwarz's Bayesian Information criteria suggest a higher goodness of fit of the Translog specification, confirmed by the likelihood ratio test. Consequently, the translog model is used in the final analysis.

Endogeneity issues

Recall that the impact of water market is represented by two variables: market existence and water trade intensity. As they are closely related, we run the analysis using market existence and trade intensity separately. However, these two market variables can be endogenous regressors. Indeed, water markets tend to be established in areas suffering from high water stress (Breviglieri, do Sol Osório and Puppim de Oliveira 2018). Thus, rainfall and potential evapotranspiration are likely predictors of the existence of water markets in a region. Besides, historically, the Murray-Darling basin hosted the first water markets in Australia and has developed an extended institutional framework for the use of water markets (Grafton, Horne and Wheeler 2016). The geographic location of a region (inside or outside the MDB) can therefore influence the probability of finding a water market.

The treatment for endogenous regressors is performed as follows. Firstly, when investigating market effect using market existence (i.e. binary variable $Market_i$), we perform a probit regression of our market existence variable on the set of explanatory variables w, which includes z, as well as MDB_i, $Rainfall_{it}$ and $PotentialEvap_{it}$. We then compute the generalized residuals (Gourieroux et al. 1987):

$$\hat{g}r_i = Market_i\lambda\left(w_i'\hat{\gamma}\right) - (1 - Market_i)\lambda\left(-w_i'\hat{\gamma}\right),$$

where $\lambda(.)$ is the inverse Mills ratio, $\lambda(.) = \phi(.)/\Phi(.)$. We then simultaneously estimate the production frontier model in (3) and (4) as explained above, but with an additional regressor corresponding to the estimated generalized residuals $\hat{g}r_i$ above. As recommended by Woolridge (2014), we test the existence for endogeneity of $Market_i$ by using a robust t-test for the significance of coefficient of $\hat{g}r_i$ in this regression. This analysis allows to test the validity of our first hypothesis H1.

Secondly, when we study the market effect using our trade intensity variable (a continuous variable), we first run a linear regression of the latter on its potential determinants instead. Note that two types of trade intensity are employed here, temporary rights and permanent rights. Then, the production frontier model in (3) and (4) is estimated with an additional regressor which is the residuals of the trade intensity regression. This analysis allows to test the validity of our second hypothesis H2.

Results

Results from the probit model (for market existence), the linear regressions (for market intensity) and the test for endogenous regressors are reported in Appendix B. The robust t-test (Woolridge 2014) shows that the generalized residual's coefficient is not significant at the 5% level, indicating that $Market$ is not subject to endogeneity. The same conclusion applies to water trade intensity (for both temporary rights and permanent rights): the residuals' coefficient of trade intensity is not significant based on the robust t-test. Therefore, in the final regressions we consider that market existence and trade intensity are exogenous regressors.

Questioning H1 about market existence and technical efficiency of agricultural production

First, we ran the analysis by including our market existence variable in the stochastic frontier conditional mean inefficiency model. The frontier estimation results appear in table 1.

Table 1. Stochastic Frontier Estimation of the Australian Agricultural Production Using Market Existence, 2010-2017.

	Total agricultural production	
Variable	Coefficient	Std. Error
Total agricultural area	1.541***	0.531
Total water use	0.731	0.447
Total water use (squared)	0.00663	0.0108
Total agricultural area (squared)	-0.0286	0.0282
Interaction	-0.0546**	0.0231
Intercept	-0.134	1.389
Number of observations	302	
AIC	447.9	
BIC	492.4	
Log-likelihood	-211.9	

Note: Significance levels: ***1%, **5%, *10%.

Agricultural area has a significant positive impact on agricultural production, while the parameter of water use is positive but not significant. The interaction between water use and agricultural area has a significant negative impact, indicating some substitution between these two inputs. However, the size of this effect is much lower than the impact of agricultural area.

Following the frontier estimation, we generated mean regional efficiency scores through $\{\exp(-u_{it}|e_{it})\}$. Table 2 reports the 5 highest and 5 lowest scores. Non-parametric mean comparison tests were applied in order to identify distinctive characteristics of the 5, 10 and 15 regions showing the highest efficiency levels. Results from Kruskall-Wallis tests appear in table 3.

Table 2. Five Highest and Five Lowest Efficiency Scores (exp[-u|e]) Following a Translog Specification, Averaged over 2011-2017.

NRM region	Mean Efficiency (exp{-u|e})
Five highest efficiency scores:	
Avon	0.915
Riverina	0.887
Port Philipp and Westernport	0.882
North West NSW	0.881
Glenelg Hopkins	0.866
Five lowest efficiency scores:	
SA Arid Lands	0.198
Kangaroo Island	0.148
Cape York	0.040
Cooperative Management area	0.033
Alinytjara Wilurara	0.014

Table 3. Results from Kruskall-Wallis Mean Comparison Tests on Groups Formed by the 5, 10 and 15 Regions Showing the Highest Efficiency Score.

Variable	Top 5	Top 10	Top 15
Mean yearly temperature (°C)	-2.53***	-1.61**	-2.02***
Mean yearly rainfall (mm/year)	-	-193.41***	-150.92*
Daily potential evapotranspiration	-0.47***	-0.30**	-0.33***
Total agricultural production (million AUD$)	7.46***	6.21***	6.26***
Total agricultural area (million ha)	-	-	-
Total water use, (GL)	-	33.50**	-
Probability to be located in MDB (%)	-0.23**	-0.18**	-
Probability that a water market exists (%)	0.19**	0.19***	0.22***
Extra temporary water volume bought (GL)	-22.20**	17.21***	-
Extra permanent water volume bought (GL)	-	-	-

Notes: Each parameter can be interpreted as the mean difference between observations in the selected group (top 5, 10 or 15 regions with the highest efficiency levels) in terms of the considered variable (left column). Significance levels: ***1%, **5%, *10%.

On average, high efficiency regions are subject to lower temperatures (-1.61 to -2.53 °C) and potential evapotranspiration (-0.30 to -0.47 mm/day). They also produce AUD$6.2 million to AUD$7.5 million more in terms of production value. Interestingly, the probability of finding a water market is about 20% higher among the most efficient regions. Agricultural area, rainfall or variables measuring the intensity of market transactions do not appear to be clear distinctive characteristics. Thus, mean comparisons tests seem to support H_1 (technical efficiency is higher where water markets can be found) but not H_2 (more transactions imply a higher technical efficiency). Evidence supporting the validity of H_1 was also found in the conditional mean inefficiency model as reported in table 4.

Table 4. Results of the Mean Conditional Inefficiency Model Using Market Existence, 2011-2017.

	Technical inefficiency	
Variable	Coefficient	Std. Error
Rainfall	0.805*	0.421
Potential evapotranspiration	0.0158	0.42
Market existence	-2.249***	0.784
Intercept	1.435*	0.838
σ_u	-0.435	0.426
σ_v	-3.541***	0.366
Number of observations	302	
AIC	447.9	
BIC	492.4	
Log-likelihood	-211.9	

Note: Significance levels: ***1%, **5%, *10%.

The existence of a water market is found to decrease the overall inefficiency, confirming the mean comparison test results and supporting the validity of H_1. Potential evapotranspiration is expected to increase water use, thus decreasing technical efficiency if water use is set constant. However, it also provides clear incentives for technical efficiency investments. In our case, no clear association was found between potential evapotranspiration and efficiency. Rainfall has an ambiguous impact on agricultural productivity: on one side, it increases a crop's access to water, therefore facilitating its development. On the other side, it increases disease risk and therefore decreases crop yield (Webb 2006). In the Australian agricultural sector, the latter effect seems to be predominant, as rainfall is associated with a higher inefficiency.

Questioning H2 about water trade intensity and efficiency of agricultural production

In order to test the validity of H_2, the stochastic frontier with conditional mean inefficiency model was ran while including two proxies for water trade intensity instead of market existence. The total volumes of temporary and permanent water rights bought in each region were used as indicators of the temporary and permanent water trade intensity. Results from the frontier estimation are reported in table 5 below.

As few observations related to the intensity of water market transactions were available, results from the water trade intensity analysis were found less stable than results related to market existence. Some parameters of the production frontier were found insignificant using the full translog specification. We suggest that a potential explanation is the high correlation (.9) between the squared inputs terms and the input variables. Results from the conditional mean model are summarized in table 6.

Table 5. Stochastic Frontier Estimation of the Australian Agricultural Production Using Water Trade Intensity, 2010-2017.

	Total agricultural production	
Variable	Temporary rights	Permanent rights
Total agricultural area	2.584**	2.450***
	(1.007)	(0.675)
Total water use	0.949	-0.284
	(1.419)	(0.979)
Total water use (squared)	0.0227	0.0193
	(0.0187)	(0.0291)
Total agricultural area (squared)	-0.0468	-0.0821**
	(0.0576)	(0.0341)
Interaction	-0.0913	-0.00445
	(0.0799)	(0.0361)
Intercept	-10.46	-0.497
	(7.662)	(0.768)
Number of observations	201	148
AIC	243.2	183.0
BIC	282.9	218.9
Log-likelihood	-109.6	-79.49

Note: Standard errors in parentheses. Significance levels: ***1%, **5%, *10%.

Table 6. Results of the Mean Conditional Inefficiency Model Using Water Trade Intensity, 2011-2017.

	Technical inefficiency	
Variables	Temporary rights	Permanent rights
Rainfall	-0.273	0.799
	(0.405)	(0.526)
Potential evapotranspiration	1.585*	-0.416
	(0.932)	(0.632)
Water trade intensity (Vol. of water bought)	-20.76	-0.00789
	(60.03)	(0.0420)
Intercept	-3.774**	-0.106
	(1.862)	(1.082)
σ_u	-6.492	-0.646
	(17.57)	(0.733)
σ_v	-1.739***	-3.283***
	(0.238)	(1.039)
Number of observations	201	148
AIC	243.2	183.0
BIC	282.9	218.9
Log-likelihood	-109.6	-79.49

Note: Standard errors in parentheses. Significance levels: ***1%, **5%, *10%.

The parameters of trade intensity variables are insignificant across all specifications. This result holds when we consider temporary or permanent trade. Thus, we find no evidence supporting the validity of H_2: a higher trade intensity is not associated with a higher efficiency between 2010 and 2017 in Australian NRM regions, according to our stochastic frontier estimation.

Overall, our results are in line the expectations formulated by the literature on water market impacts (Bjornlund 1999; Grafton, Horne and Wheeler 2016), as well as the predictions made by general equilibrium modelling (Peterson et al. 2005; NWC 2012). Our findings confirm that these impacts can be noticed at a regional aggregated level: the existence of water markets in a region is associated with higher technical efficiency scores according to our stochastic frontier estimation between 2010 and 2017. However, we find no association between a higher intensity of market trade and efficiency. Thus, we find evidence supporting the validity of H_1 (the existence of water markets in a region is associated with a higher efficiency) but not H_2.

Robustness tests

In order to improve the validity of our results, different robustness and sensitivity tests were conducted. Differences in regions' profiles in terms of agricultural production could explain some variations in technical efficiency. In order to avoid such a bias, additional estimations were made incorporating categorical variables reflecting the part of agricultural production dedicated to broadacre crops, horticulture and livestock. Results can be found in Appendix C and are similar to those from the main estimation: market existence positively influences technical efficiency, while no significant impact is found of trade intensity. Besides, the prevalence of horticulture and broadacre crops increase the probability of water markets' existence in a region, as opposed to regions dominated by livestock production.

We considered a potential bias in relation to the collection methodology for some of the variables used. All variables sourced from the ABS have been collected by random sampling. However, in 2015, the ABS has changed its data collection methodology by excluding economic agents whose (agricultural) income is under AUD$40 000 from the collection process (this threshold was AUD$5000 previously). Thus, the two last years of our sample are potentially affected by this methodological change. In order to avoid the potential bias arising from this new random sampling methodology, Kruskall-Wallis mean comparison tests by groups were applied to all variables sourced from the ABS, in order to see whether a significant difference could exist. All tests were negative (no significant mean difference), except for the extra volume of permanent water bought, where a significant increase in trading was detected after 2015. We suggest that this difference does not undermine our results in a major way for two reasons: first, an alternative proxy free of the previous problem (no significant mean difference after 2015) was used instead: the total cost of extra permanent water bought. The estimation generated identical results (no significance of permanent water trade intensity and parameters of a similar magnitude). Second, the results of both estimations related to permanent water trade intensity are similar to those using temporary trade, that show no significant mean difference after 2015.

VIFs were generated using linear regressions after the frontier estimation. No VIF under 5 was detected in the conditional mean inefficiency model. However, the squared input and interaction terms related to the Translog specifications generated high VIFs. Regressions excluding squared input terms and the Translog interaction (Cobb-Douglas specifications) were also tested. Similar results were found.

Finally, in order to check the influence of potential outliers, Cooks distances and leverages were generated following linear regressions of inefficiency scores. No Cook's distance over 1 was detected. However, we ran the analysis while excluding observations whose leverage values were found over the (K+1/N) threshold. The results were qualitatively the same.

Short-term optimal prediction of water use

In this Section, we perform short-term predictions of the model based on our empirical estimates. Note that the profit of farmer i (a representative farmer) is $\pi_i = pY_i - r_a Area_i - r_w Wateruse_i$, where Y_i is the production (given by the translog function estimated above), r_a the unit cost of land, and r_w the unit cost of water. We assume that farmers are price-takers and cannot modify agricultural land surface in the short-run, hence $Area_i = \overline{Area}_i$. The latter assumption is quite reasonable because farmers cannot sell, buy or rent his land easily in the short term.

Taking the first-order optimal condition of the profit maximization with respect to water, we have

$$r_w = p\frac{\partial Y_i}{\partial Wateruse_i}.$$

This gives the following condition (using the parameters of the previous econometric model):

$$\frac{r_w Wateruse_i}{pY_i} = \beta_2 + 2\beta_4 lnWateruse_i + \beta_5 ln\overline{Area}_i,$$

which indicates the share of water use in output value (left-hand side term) is a linear function of inputs (right-hand side). Note that this calculation does not directly depend on technical inefficiency. The previous condition can be rewritten equivalently as

$$\frac{r_w Wateruse_i}{pY_i} - 2\beta_4 lnWateruse_i = \beta_2 + \beta_5 ln\overline{Area}_i.$$

Therefore, with the estimated values for $\beta_2, \beta_4, \beta_5$, and given the market price of water and the output price, we can predict the quantity of water necessary to produce the quantity of output Y_i, for the land surface fixed at the value $\overline{Area}_i$.

Using the estimated coefficients from the model and solving the equation above, we show in figure 4 the regions that use water in their production optimally (i.e. they use a quantity of water that satisfies the first-order condition above) or not optimally. The calculation is based on data observed in 2016 and temporary water price, corresponding to 25 regions. The diagonal line corresponds to the situation where optimal predicted quantity is equal to the observed quantity of water, indicating that the observed quantity of water used is optimal. The figure also shows regions that use water lower (observations above the diagonal) or higher (below the diagonal) than the optimal levels.

According to our prediction, NRM regions such as East Gippsland (VIC, region 15) and Northern and Yorke (43) consume more water than the optimal level. Both regions use a low amount of water in comparison to other Australian regions, between 7200 and 9000 ML/year, and figure among the 10 regions using the lowest amount of water in the country. However, they differ in their output size and temporary water market use: East Gippsland produces about AUD$210 millions worth of output and is ranked the 58th producer in the database (out of 64). Barely 5% of the total water used in the region is bought through temporary water markets, in a context where annual rainfall is largely superior to annual evapotranspiration. In contrast, Northern and Yorke (QLD) is the 19th biggest agricultural producer in Australia with an annual production worth about AUD$1.43 billion, and more than 32% of the total regional water use is bought through water markets. Hydric deficit is marked in the region (about -265 mm). In view of their low water uses, their 'excessive' water consumption can be related to the fact that these regions do not appear to be constrained by water resources availability. Besides, their different allocative and technical efficiencies of agricultural production explain different levels of output values.

Inversely, Border Rivers (QLD, region 4), the Murray (NSW, region 29) and Riverina (NSW, region 47) use less water than the optimal level. These three regions are all among the biggest agricultural producers in Australia: they respectively stand 12th, 16th and 1st in terms of monetary value generated by agricultural production. They are also among the biggest water users in Australia (8th, 4th and 2nd regions in terms of total water use). This could suggest that water use in such regions is constrained by resource availability, preventing them to use additional water that would be needed to reach the optimal water use in the context of a widely developed agricultural sector. Facing these constraints, all 3 regions resort to temporary water markets to buy more water: although 20% of the water used in Riverina and about 15% in East Gippsland was bought on the market, while Border Rivers has a limited use of temporary water markets (2.55% of total water used is exchanged on average).

Finally, regions as Burdekin (QLD, 6), Condamine (QLD, 11) and the SA Murray-Darling Basin (49) lie on the frontier: they use an amount of water considered as optimal by our model, i.e they maximize their regional income per volume of water used. These regions tend to generate significant but moderate output values (they produce AUD$1.20 to 1.75 billion on average) and show relatively high water uses. Interestingly, very regions are subject to some of the most important hydric deficits[2] (-230 mm to -429 mm annually) in Australia.

The analysis in this Section helps draw some recommendations about regional water use in the short term. For regions such as East Gippsland and Northern and York, a reduction of water use appears to be necessary to achieve a higher production efficiency. On the

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[2] We measure here hydric deficits through the difference between annual rainfall and annual potential evapotranspiration. Thus, a negative figure indicates that annual evapotranspiration is higher than annual rainfall.

contrary, other regions like Border Rivers, the Murray and Riverina, an increase in water use (e.g. by relying more on market transactions) could be expected in order to improve their efficiency. Note that the latter regions are located within the Murray-Darling Basin, where more than 50 per cent of the annual run-off is already extracted and ongoing efforts are made to reduce such extractions (Grafton 2019) and reallocate water towards the environment (Williams and Grafton 2019), under then amended 2018 MDB Basin Plan. In view of this context, we stress that any water use increase in such regions should be made through market transactions (i.e. buying water from lower efficiency regions), and not by increasing water extractions. Besides, such transfers should carefully consider the potential resulting externalities, such as salinity impacts (Qureshi et al. 2011).

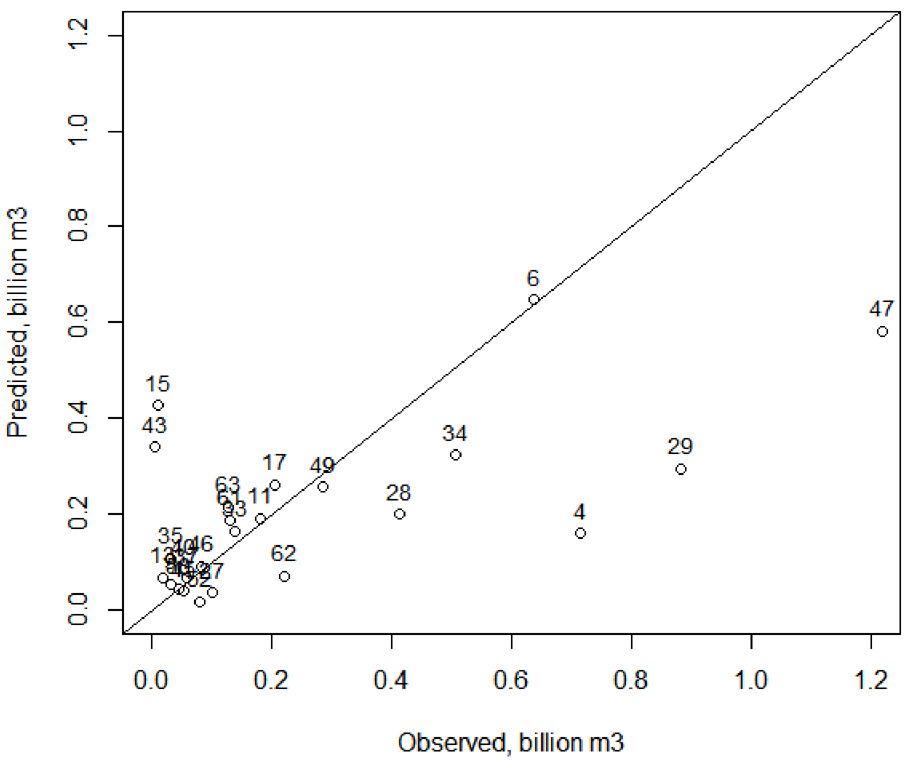

Figure 4. Optimal quantity versus observed quantity in 2016.

Conclusion

The purpose of this article was to question the effect of water markets on water use efficiency in Australia, as a complementary analysis to the General Equilibrium approach (Peterson et al. 2005) that has generally been used in that matter. To our knowledge, this article is the first to use a stochastic frontier approach and regional data in order to measure the impact of water market's existence and trade intensity in Australia. We gathered a database crossing agricultural data from the Australian Bureau of Statistics (ABS), climatic data from the Bureau of Meteorology (BoM) and market data from the National Water Commission (NWC). We find a positive impact of the existence of water markets in a NRM region on technical efficiency in the Australian agricultural sector, between 2011 and 2017. However, we found no evidence showing that a higher trade intensity would be associated to a higher water use efficiency.

Regarding further extension, as we measured market impacts at an aggregated regional level, it would be interesting to conduct the analysis at a farm level, which would require more detailed data. A less aggregated level of analysis using more detailed data to control for other production inputs like labor and capital would be of interest to check our results, given the fact that the economic benefits associated with water markets will be of major interest to the future debates on water markets and policy.

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Appendices

Appendix A. Summary Statistics and Data Sources.

Variable	Description	Source	Obs.	Mean	Std. Dev.	Min	Max
Total agricultural production	Total annual agricultural production value, deflated using the annual ABARES index of prices received by irrigators (100m$)	ABS; ABARES	302	6928.63	4152.45	18.63	2000
Total water use	Total annual water use dedicated to agricultural production (GL)	ABS	302	186.29	275.44	0.144	1499.93
Total agricultural area	Total area used for agricultural production (1000 ha), yearly.	ABS	302	7086.53	13100	0.89	71400
Rainfall	Mean yearly rainfall at the region level. Computed as an average of monthly rainfall measurements in 5 to 10 stations across each region.	BoM	302	723.94	404.07	169.76	2888.62
Potential evapotranspiration	Mean potential evapotranspiration per day in each region. Computed based on the guidelines published by Allen et al. (1998)	BoM; Allen et al.(1998)	302	1.97	0.73	0.79	3.73
Mean temperature	Mean annual temperature. Computed based on the mean monthly temperature estimates of about 5 stations across each NRM region. Mean monthly temperature based on the average of mean minimum temperature and mean maximum temperature.	BoM; Allen et al.(1998)	302	18.27	3.99	12.49	27.20

MDB	Dummy variable equal to 1 for regions located within the Murray-Darling Basin. Defined by crossing GIS data on the MDB and NRM regions boundaries	Murray-Darling Basin Authority (MDBA); ABS	302	0.32	0.47	0	1
Market existence	Dummy variable equal to 1 for regions where at least one (temporary or permanent) water trade has been recorded in the current or past fiscal years.	ABS	302	0.85	0.36	0	1
Volume of extra temporary water bought	Volume of extra temporary water bought in each region, per year. Expressed in gigaliters (GL).	ABS	201	39.29	77.11	0.01	479.35
Volume of extra permanent water bought	Volume of extra permanent water bought in each region, per year. Expressed in gigaliters (GL).	ABS	148	3.47	5.12	0.00	32.09

Note: ABS: Australian Bureau of Statistics; ABARES: Australian Bureau of Agricultural and Resource Economics and Sciences; BoM: Bureau of Meteorology.

Appendix B. Results from the First Step Probit and Linear Regressions.

Variable	Market existence (probit)	Temporary water bought (linear regression)	Permanent water bought (linear regression)
MDB	0.308	0.0910***	2.333**
	(0.210)	(0.0104)	(0.963)
Rainfall	0.934***	-0.000666	0.0887
	(0.268)	(0.0119)	(1.135)
Potential evapotranspiration	-0.931***	-0.0132*	-0.243
	(0.137)	(0.00698)	(0.659)
Intercept	2.222***	0.0335**	2.953**
	(0.359)	(0.0159)	(1.484)
Number of observations	316	202	149
R-squared		0.322	0.048
AIC	239.0	-534.4	908.4
BIC	254.0	-521.1	920.4

Note: Standard errors in parentheses. Significance levels: ***1%, **5%, *10%.

Appendix C. Results Incorporating Categorical Production Variables.

Table C1. Stochastic Frontier Results Incorporating Categorical Variables, Market Existence.

	Total agricultural production	
Variable	Coefficient	Std. Error
Total agricultural area	0.908*	0.467
Total water use	1.343***	0.348
Total water use (squared)	-0.00137	0.0113
Total agricultural area (squared)	0.00494	0.0192
Interaction	-0.0781***	0.0215
Horticulture	0.324	0.459
Broadacre	0.683**	0.279
Intercept	-0.807	3.639
Number of observations	302	
AIC	452.1	
BIC	504.0	
Log-likelihood	-212.0	

Note: Significance levels: *** 1%, * 5%, * 10%.

Table C2. Technical Inefficiency Determinants, Market Existence.

	Technical inefficiency	
Variable	Coefficient	Std. Error
Rainfall	0.0935	0.193
Potential evapotranspiration	0.477*	0.258
Market existence	-0.900***	0.239
Intercept	-0.0227	0.514
σ_u	-6.124*	3.641
σ_v	-1.439***	0.163
Number of observations	302	
AIC	452.1	
BIC	504	
Log-likelihood	-212.0	

Note: Significance levels: *** 1%, * 5%, * 10%.

Table C3. Stochastic Frontier Results Incorporating Categorical Variables, Water Trade Intensity.

	Total agricultural production	
Variables	Temporary rights	Permanent rights
Total agricultural area	1.998	2.237**
	(2.987)	(0.914)
Total water use	0.0221	-0.0455
	(1.370)	(1.145)
Total water use (squared)	0.00945	0.00981
	(0.0176)	(0.0362)
Total agricultural area (squared)	-0.0614	-0.0740*
	(0.0851)	(0.0425)
Interaction	-0.0152	-0.00631
	(0.0639)	(0.0354)
Horticulture	0.0765	0.259
	(0.317)	(0.438)
Broadacre	0.133	0.264
	(0.314)	(0.426)
Intercept	1.309	-0.395
	(28.93)	(0.987)
Number of observations	201	148
AIC	228.8	184.6
BIC	275.0	226.5
Log-likelihood	-100.4	-78.29

Note: Standard errors in parentheses. Significance levels: *** 1%, ** 5%, * 10%.

Table C4. Technical Inefficiency Determinants, Water Trade Intensity.

	Technical inefficiency	
Variables	Temporary rights	Permanent rights
Rainfall	0.708*	0.743
	(0.406)	(0.588)
Potential evapotranspiration	-0.237	-0.282
	(0.536)	(0.691)
Water trade intensity (Vol. of water bought)	-10.38	-0.0141
	(11.23)	(0.0432)
Intercept	-0.0418	-0.112
	(0.921)	(0.859)
Usigma	-0.497	-0.733
	(0.740)	(0.876)
Vsigma	-4.153	-3.508***
	(2.852)	(1.266)
Number of observations	201	148
AIC	228.8	184.6
BIC	275.0	226.5
Log-likelihood	-100.4	-78.29

Note: Standard errors in parentheses. Significance levels: *** 1%, ** 5%, * 10%.

Table C5. First Step Probit and Linear Regression Estimations Incorporating Categorical Variables.

Variable	Market existence (probit)	Temporary water bought (linear regression)	Permanent water bought (linear regression)
Murray-Darling Basin	0.0767	0.0928***	2.818***
	(0.234)	(0.0109)	(1.074)
Rainfall	0.962***	-0.00226	0.182
	(0.340)	(0.0121)	(1.141)
Potential Evapotranspiration	-0.712***	-0.0115	0.0207
	(0.137)	(0.00729)	(0.702)
Horticulture	2.737***	0.0190	-1.262
	(0.678)	(0.0280)	(2.541)
Broadacre	2.214***	-0.00814	-2.837
	(0.447)	(0.0219)	(2.469)
Intercept	0.803*	0.0292	3.275*
	(0.439)	(0.0178)	(1.678)
Number of observations	316	202	149
R-sq		0.326	0.056
AIC	203.9	-531.4	911.1
BIC	226.4	-511.6	929.1
Log-likelihood	-95.95	271.7	-449.5

Note: standard errors in parentheses. Significance levels: *** 1%, ** 5%, * 10%.