Do water markets improve agricultural productivity? Water market impacts on technical efficiency in the grape production sector in the Murray-Darling Basin, Australia

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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 efficiency in water resources allocation. The Murray-Darling Basin in Australia hosts some of the most advanced water markets in the world (Grafton, 2011). In this paper we analyze their impacts on technical efficiency in the Australian Grape production sector. We gathered a database on agricultural production, inputs, climatic variables and the existence of a water market at a regional level. Using a stochastic frontier model and a control function approach, we find a significant positive impact of water markets on technical efficiency.

Introduction

In 2016, the World Economic Forum held in Davos published the Global Risks Landscape 2015[1]. Among all the risks presented the report rank water crisis as the most important risk in terms of potential impact. Behind this acknowledgement, a fact: demographic pressures and the expected impacts of climate change endanger the balance between water supply and demand, while the means of increasing water supply become more and more expansive.

In this context, water markets have emerged as a potential tool to deal with water scarcity. Such markets can be defined as "a system of formal rules and regulations that govern the buying, selling and leasing of water use rights (…) that are ideally traded independent of land titles" (Debaere et al., 2014). They can be used in a given sector, as agriculture; or they can allow inter-sectoral trades, as in the case of rural to urban transfers. By reallocating water to the most productive activities (Hodgson, 2006), from low-value to higher valued uses (Dinar et al., 1997), markets are expected to foster a more efficient use for water. Instead of increasing the available supply, they are expected to reallocate water in a more efficient way.

Australia is a perfect example of such a situation. The South-eastern corner of the Australian territory is subject to significant physical water scarcity, according to the UN (2012): in their words, water resources development is approaching or has already exceeded sustainable limits. Australia has developed water markets since the early 1980s, and extended their importance in 1994, when a cap on total water extractions was introduced, in parallel with a separation between land titles and the water resources that were previously bundled to it. Historically, water markets appeared first within the Murray-Darling Basin (MDB), located within the South-eastern corner of Australia. It developed through progressive reforms, and experienced a massive increase in transactions after 2007. Grafton et al. (2010), in a comparative study of water markets in different parts of the world, described water markets in the Murray-Darling Basin as the most advanced existing water markets.

This context strengthens the interest of studying water markets in the area, as the global occurrence of water stress is likely to increase in the upcoming decades: Australia, and the Murray-Darling basin in particular, presents a laboratory to the use of economic and market tools to face situations of water scarcity. The aim of this study is to question the impact of

[1] http://reports.weforum.org/global-risks-2015/top-10-infographics/, as of 26/01/2016 at 15:12 pm

such tools on agricultural productivity, through water allocation efficiency. We based our analysis on agricultural, climatic, and market data. Do water markets foster improvements in the efficiency of water use, and thus in agricultural productivity in the Australian context? In other words, did the market reallocate water to the highest value-producing users? The approach chosen to address this question is to analyze the impact of water markets using stochastic frontier and the concept of technical efficiency. We applied our model to the grape production sector specifically, and further tested it on agricultural commodities globally.

Literature review: water market impacts on water allocation efficiency

Markets have been praised 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. Resorting to the private sector in the field of water allocation decisions was for example advocated by Milliman (1959), or Hartman and Seastone (1970).

Different empirical studies dedicated to water market impacts simulate their existence to estimate potential benefits. Vaux and Howitt (1984) simulate 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 $66 million for the year 1980, and are expected to increase to $220 million for the year 2020. Geographically close to this first study, Dinar and Letey (1991) estimate profit functions for farmers in the San Joaquin Valley and simulate the ability to trade water in their model. 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 a general equilibrium approach 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 ($555 million in a year subjected to important water scarcity, and $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) choose this approach and analyze transactions from water markets in Chile in the agricultural sector. They compare water values determined by crop budget to prices included in water trades. They find 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 relate them to the characteristics of the irrigators involved in the trade. He finds that water was in average moving towards more efficient buyers that were also growing higher-valued crops. However, he finds no evidence that the buyers use their newly acquired water to increase their cultivated area. Brooks and Harris (2008) analyze data from three trading zones in northern Victoria to determine consumer and producer surplus. They find surpluses averaging $20 000 a week in the Greater Goulburn area. The potential for gains from trade is also empirically shown in Australia by Nauges, Wheeler and Zuo (2015) that estimate marginal contribution of irrigation water to profit at $547/ML and $61/ML, for horticulture and broadacre crops respectively.

Besides gains from trade, different empirical studies showed that water markets are used by irrigators to improve their risk management. Farmers experiencing a high variability in profits have incentives to buy more on water markets (Cristi, 2007; Calatrava and Garrido, 2005). This has been shown empirically in Australia, particularly in the horticultural sector (Zuo, Nauges and Wheeler, 2015) as permanent trees and vines could die if they are exposed to excessive water stress (Loch et al., 2012). In that sense, water markets are clearly beneficial to the agricultural sector in terms of risk management. farmers tend to be risk averse, under different modalities (Neauges, Wheeler and Zuo, 2015). Water markets are therefore expected to improve farmer's ability to manage their risk.

In parallel to these empirical estimates, 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., FAO 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, the potential for externalities is important. 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 Fernandez, 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. Furthermore, 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 relation to these market failures, different authors notice the very limited development of water markets in terms of transactions between 1980 and 2000, mainly in the United States. Some attempt to explain this phenomenon, as Rosen and Sexton (1993) who suggest the low level of transactions is due to a lack of cooperation between market actors and operational institutions actually owning the water. Saliba et al (1987) also question the limited amount of water trade that was undertaken at the time, as compared to the potential benefits that could be realized from it according to Vaux and Howitt (1984). They conclude that the interdependencies and the public good characteristics of water make perfectly competitive markets purely infeasible in practice.

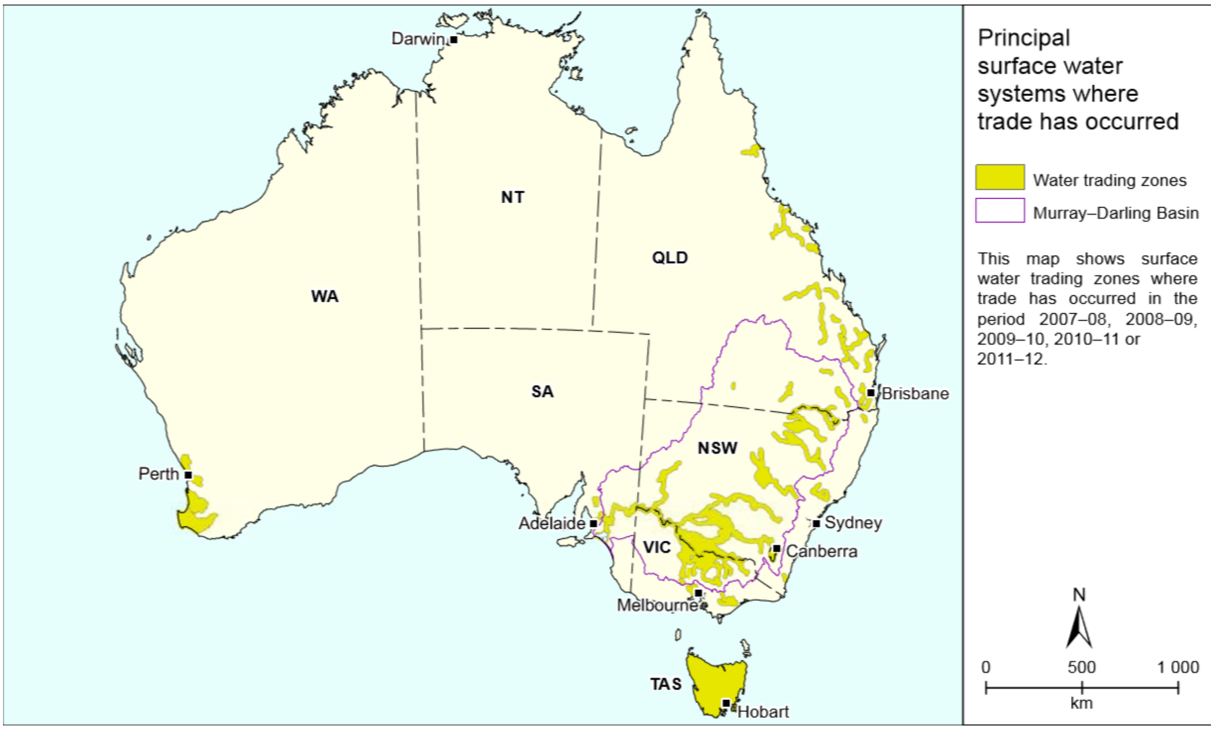
This study hopes to contribute to the literature dedicated to water market’s economic impacts. As described in the preceding review, besides improving farmer’s ability to manage their risk, water markets are expected to reallocate water towards higher value users and higher value sectors. In this process, the global productivity of agriculture is therefore expected to increase, as water becomes more efficiently used. In other words, in the presence of water markets, one unit of water is expected to bring more production. This hypothesis is challenged by the different market failures described by the literature, and has to be studied in a context of risk adversity. We attempt to test it empirically using a stochastic frontier model at a regional level, and Australian data on market existence, agricultural production, inputs, and climatic conditions.

Context

Water markets in Australia

There is no global water market in Australia. Water trade occurs in distinct markets spread around the country. Water trade is, for logistical and juridical reasons, only possible between hydrologically connected zones[1]. In particular, the Murray-Darling Basin (MDB) represents more than 60 % of the Australian irrigated surface and over 80 % of the Australian water trade (NWC 2011). The market was historically created around the agricultural sector in the MDB (Maziotis et al., 2013) and it is where water trade is the most developed and established, as illustrated by the National Water Commission (NWC):

Figure 1: Occurrence of water trading in Australia, 2007-08 to 2011-12

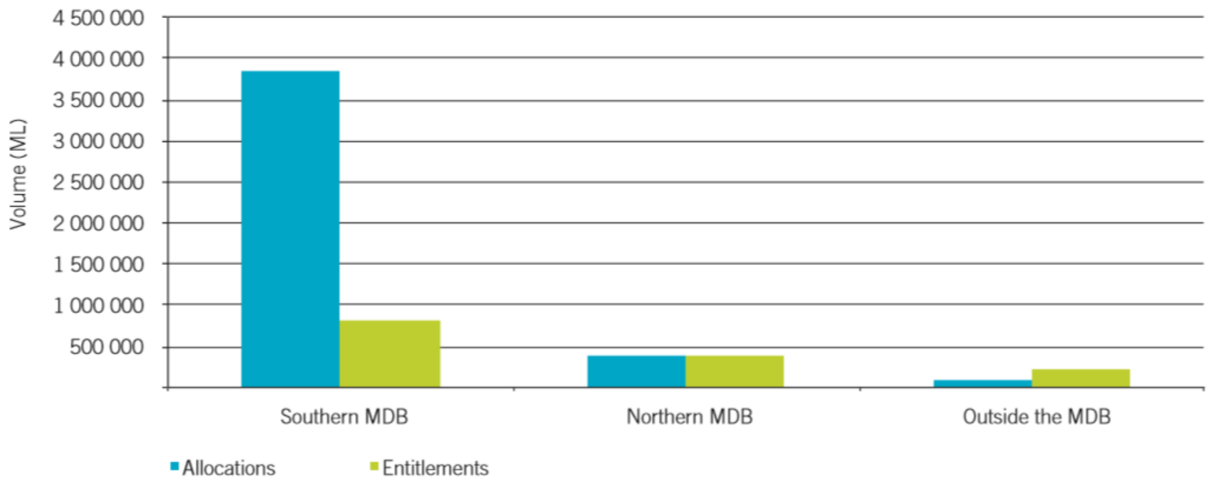


Source : reproduced from NWC 2013, Figure 1.6

The basin is represented here as the area within the continuous line in the South-East corner of Australia. It involves parts of four Australian States: New South Wales, Victoria, Queensland, and South Australia. It also includes the Australian Capital Territory. As the basin is subject to a climate favoring irrigated agriculture in comparison with the semi-arid climate found northwards, agriculture covers 67% of its territory. The MDB is clearly facing a water scarcity situation. In 2015, the ratio of water demand to available water resources was superior to 0.4 in most of the basin's area, defining a "high" water stress (UN Water report 2015[2]). This and the prevalence of irrigated agriculture contribute to explain the emergence of water markets in the area: as noted by Debaere et al. (2014), a market for water resources potentially appears when water demand approaches water availability.

Different water market regions are defined by the National Water Commission "Water market reports" in Australia (NWC 2013). Inside the Murray-Darling basin, the southern-connected MDB region is the most active water trading area in the country. It is represented by the green area in the southern half of the MDB in Table 1. The northern half of the basin contains the northern MDB region, graphically represented in Table 1 as well. The third region is a gathering of different areas where water trade is occurring. The dominant market region, in terms of volume traded, is undeniably the southern MDB segment, as suggested by the following table published by the National Water Commission:

Figure 2: Water trade in three market regions, 2011-12



Source: reproduced from figure 1.7 in NWC (2013)

The important volume of water trade occurring in the southern MDB brought Grafton et al. (2010) to describe water markets in the Murray-Darling Basin as the most advanced in the world.

[2] Source : UN Water report 2015, cited by Le Monde (March 20th, 2015)

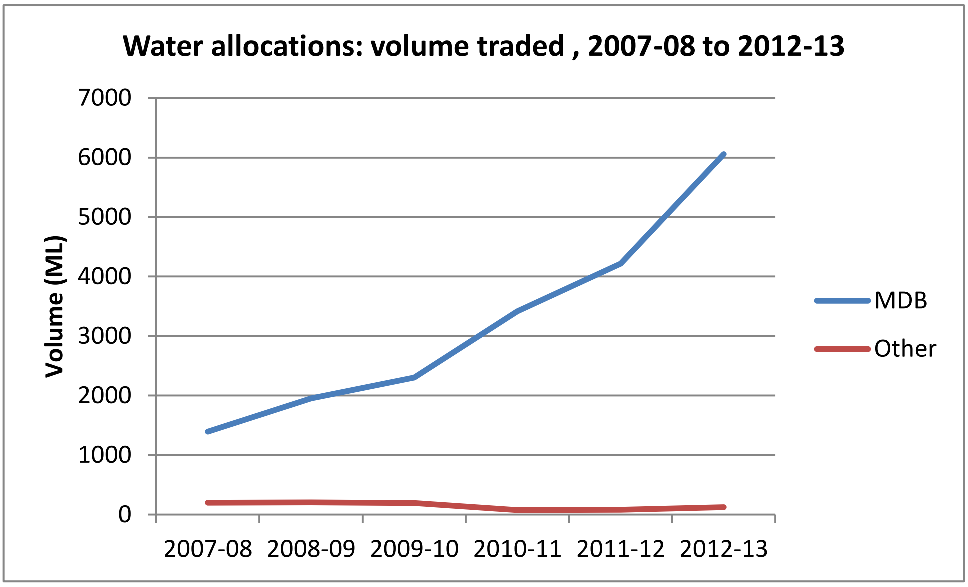
80% of the world's water is consumed by agriculture (UN, 2009), and the MDB is no exception to this phenomenon. As a result, water markets were historically meant to reallocate water resources in the agricultural sector, and the most important actors of water trade are irrigators. However, a number of other actors are involved in the process of exchanging water rights in Australia. This includes 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. All of 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, the most important being the following:

- 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, finally, 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.

In parallel to this process, transactions in the MDB increased in a major way between 2007-08 and 2012-13. The following figure illustrates the trend in allocation trading, the exchange of temporary rights to water:

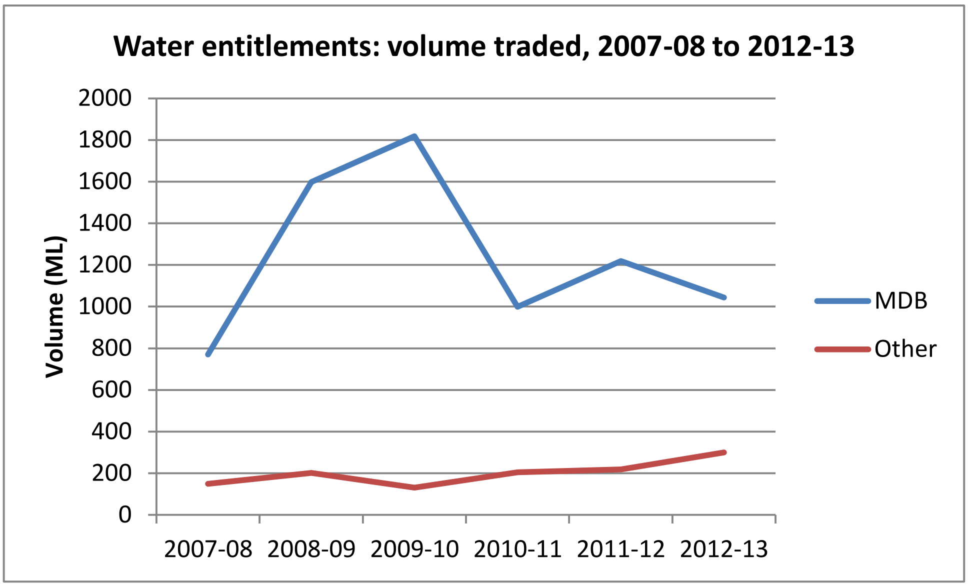
Figure 3: Allocation trade in Australia, within and without the Murray-Darling Basin



Source: adapted from data in NWC (2014)

While allocation trading remained at a similar level between 2007-08 and 2012-13 outside of the MDB, it constantly increased in the Basin to reach a total of 6058 ML traded in the year 2012-13, more than four times its initial value of 1393 ML traded. In the entitlement market, which is the exchange of permanent rights to water, volumes traded did not follow the same pattern:

Figure 4: Entitlement trade in Australia, within and without the Murray-Darling Basin



Source: adapted from data in NWC (2014)

Although the Murray-Darling basin still distinguishes itself by the level of water trading that occurred, the precedent trend towards higher trading volumes is not as strong in the entitlement market, suggesting there is less change in permanent ownership than in temporary ownership for water in the agricultural sector.

There is therefore a massive increase in market activity following the year 2007/08 in the Murray-Darling Basin allocation markets. This change, mainly occurring in the southern connected part of the Basin, was largely intended by federal and national authorities, as water markets were established in the aim to increase efficiency in the allocation of water resources: markets are expected to allocate water towards those creating the most value with it. This can be explained by the water scarcity phenomenon affecting the Basin in the 2000s. As the Millennial Drought hit Australia in the years following 2004, with effects lasting until 2009 for certain areas in the MDB, the authorities undertook the establishment of water markets in an effort to reallocate water resources more efficiently. The aim of our study is to determine whether water markets actually fostered an increase in technical efficiency, and therefore in production, between 2007-08 and 2013-14.

Specifically, besides studying agriculture as a whole, we chose to focus on one sector: grape production. Grapes are produced in all Australian States and Territories and constitute one of the major commodities produced in Australia. This allows for comparisons between different areas across the country, and we use this opportunity. Secondly, grape production necessitates a constant access to water throughout the year, meaning that it is an almost exclusively irrigated crop. Horticulturalists have particularly strong incentives to take part to water markets when they exist, as permanent trees and vines can die if exposed to an excessive water stress (Loch et al., 2012). Grape production is therefore specifically likely to be impacted by the water market when such a market is available. Finally, grape production in Australia is produced in a relatively constant way between 2007-08 and 2013-14, our period of study. The consistency of the output's quantity enables a more robust analysis of agricultural productivities, while making reallocations of water within the grape production sector possible.

Methodology and data

The data

The data analyzed in the next sections was obtained through different sources. Most of the data available is defined at a regional level: the 54 Australian Natural Resource Management Regions, as defined by the ABS, form the geographic basis of our analysis. The following sections will present the data used in this research, along with the justification for its use in our matter of interest. Descriptive statistics for all variables described can be found in Appendix 1.

<u>Agricultural data</u>

To analyze the efficiency of water use in the grape production sector, we chose to use data relating to the value of agricultural production in the sector and to the amount of water used to generate this production. The Australian Bureau of Statistics (ABS) was the main source for this required data. The ABS reports 'Agricultural Commodities', 'Water Use on Australian Farms' and 'Value of Agricultural Production' for each year between 2007-10 and 2013-14 provided annual data on grape production, in tons and value generated for each NRM region in Australia, as well as water use in the grape production sector in the same time-period. As the cultivated area is an important factor explaining agricultural production, it has been included in our database and is expected to induce a higher level of production. Similar data concerning agricultural production as a whole was extracted from the ABS reports. The agricultural labor productivity was also derived for the year 2013-14, by relating the total agricultural production to the number of permanent agricultural employees in the agricultural sector. This indicator was used in order to control for the potential correlation between the global agricultural labor productivity and its counterpart in the grape production sector. As we could find no evidence of such a correlation, however, this variable was not used in the results presented.

Climatic data

Climate has been described as the most important determinant of agricultural productivity, mainly through its influence on temperature and water regimes (Kang et al, 2009). We therefore use rainfall and potential evapotranspiration in our analysis, in order to take these determinant influences into account. As estimates of rainfall or temperature at a NRM region level are not available, the data has been computed based on the rainfall, latitude and temperature of individual stations across Australia. The computation procedure varies according to the concerned data, and is described in the following sections.

Rainfall

The procedure used to obtain estimates of the annual rainfall for each of the 54 NRM regions between 2007-08 and 2013-14 is the following:

Step 1: 10 hydrographic stations have been defined for each region. These stations have been chosen in order for them to cover most of the region's territory, although this choice was constrained by the limited number of stations available. A list of the available stations can be found on the Australian Bureau of Meteorology's website[3].

Step 2: Monthly rainfall data between July 2007 and June 2014 was extracted for the 540 stations through the Australian Bureau of Meteorology (BoM) online database, and estimates for annual rainfall were computed from these monthly estimates.

[3] http://www.bom.gov.au/climate/data/index.shtml?bookmark=200 , as of January 21st, 2016 at 11:02 am.

Step 3: Annual rainfall for a given NRM region was defined as the average of the annual rainfall found in the 10 stations defined in step 1.

The estimates of annual rainfall used in this study are therefore based on daily observations made in 540 different stations across Australia's 54 NRM regions, between July 2007 and June 2014. 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. This second effect was described as dominant in the grape production sector by Webb (2006).

Temperature

The procedure used to obtain temperature estimates is similar to the one described earlier. However, as individual stations providing temperature observations are not as commonly available as in the case of rainfall, the number of stations selected for each NRM region was sometimes lower. As a consequence, each region is represented by 5 to 10 stations, depending on the existence of hydrometric stations recording temperature in the region and on their location. Besides, temperature is analyzed through two different monthly estimates:

- The mean maximum temperature, defined as the average of daily maximum temperatures in a given month;
- The mean minimum temperature, defined as the average of daily minimum temperatures in a given month

The mean temperature, following Allen et al. (1998), was then defined as:

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

The procedure used to obtain estimates for the mean annual temperature is therefore:

Step 1: Definition of 5 to 10 stations, geographically representative of the NRM region concerned;

Step 2: Extraction of monthly mean maximum and mean minimum temperature data for the given stations through the BoM;

Step 3: Computation of the monthly mean temperature through Equation (3);

Step 4: Computation of the annual mean temperature, defined as the average of all monthly mean temperatures in a given year, for each NRM region in each year of our analysis.

Evapotranspiration

Potential Evapotranspiration (PE) has been calculated from the temperature and latitude in the different NRM regions. Potential Evapotranspiration is a measure of the quantity of water that will evaporate and transpire from the crop, under ideal hydrometric circumstances. It is computed based on temperature and takes into account different additional factors, such as radiations that depend on the latitude of a given area. It is therefore often described as a better predictor than temperature and is widely used in the literature (see Webb, 2006 or Blanc, 2014 for examples). It is expected to increase water use, as it increases the irrigation needs to maintain a constant access to water for a given crop. The effect of evapotranspiration once water use is set constant, however, is difficult to determine.

To determine the annual potential evapotranspiration in the different NRM regions we chose to rely on the FAO Penman-Monteith equation, as recommended by the FAO (Allen et al., 1998). Some missing climatic data (wind speed, radiations, etc.) was simulated according to Allen et al.'s advice.

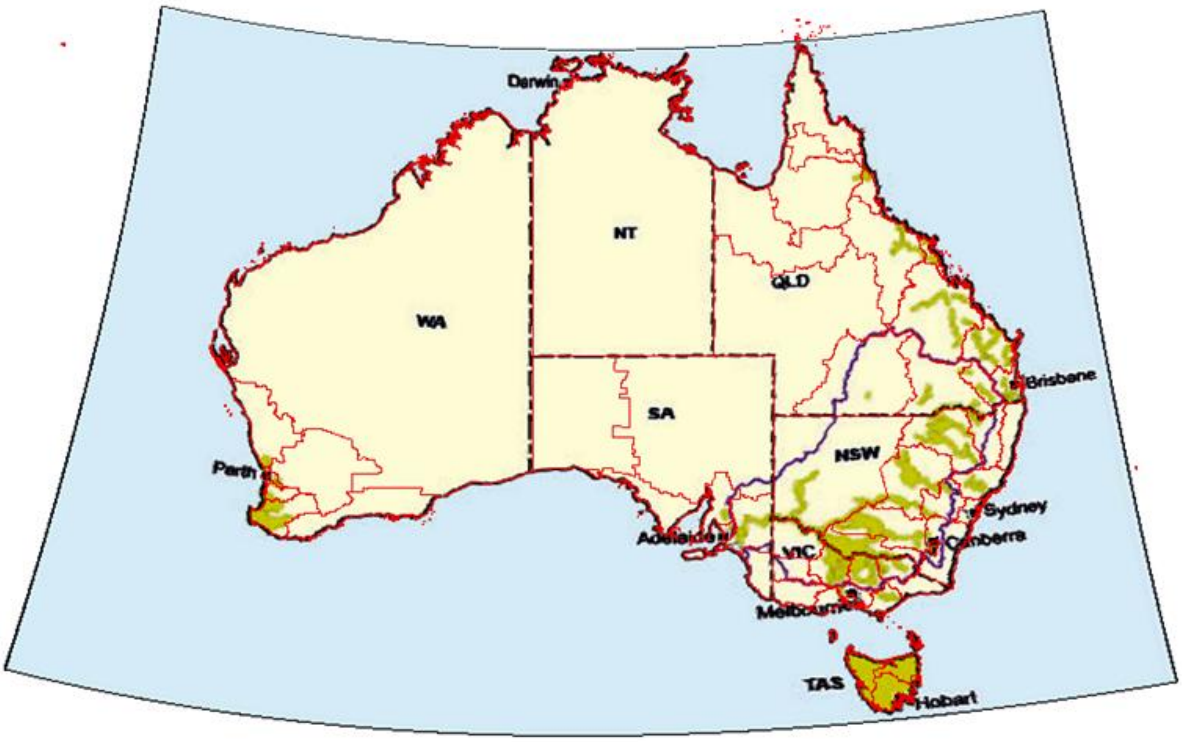
Market data

There are two types of market transactions ongoing in the Australian water markets. Entitlement trading implies the exchange of a permanent water right (i.e. the right to perceive an annual allocation for each year following the trade), while allocation trade implies the exchange of one annual allocation, for a given water year. For both categories, water markets are expected to increase water productivity and thus agricultural productivity as water is sold to the most efficient agents (Hodgson, 2006; Peterson et al, 2005).

Our data relating to market information was limited by the amount of information available, still limited at the time of our study. Nonetheless, the data on transaction volumes in Australian water markets was obtained in the National Water Commission's *Water market reports* (NWC 2013). As there is no sufficient market information available at the Natural Resource Management level, we chose to focus on the presence of water markets as a dummy variable. It is therefore important to stress the fact that we do not account for the intensity of market activity.

The existence of water market is represented as a binary variable, equal to 1 in presence of water markets and 0 elsewise. To define the presence of water markets in a given NRM region, geographic data obtained through the 2012 National Water Commission's report and a mapped representation of NRM regions in 2006, still in use in the ABS reports as of today, were crossed. As the level of aggregation used by the Australian Bureau of Statistics and the National Water Commission differ, the data was obtained by superposition. The following figure crosses NWC data on the presence of active water markets with the Natural Resource Management regions used by the ABS:

Figure 5: Market presence in NRM regions



Source: adapted from figures in NWC (2012) and FRA (2006); Map created by superposition with the ArcGIS software.

All the areas represented in green relate to zones where water trading occurred at least once between 2007-08 and 2011-12. The Murray-Darling Basin's frontiers appear in purple. The variable describing the existence of water markets was set to be 1 if trading occurred at least once in the corresponding area, and 0 elsewise.

Econometric Framework

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, for example, Nguyen Phu and Nguyen Tho-Te (2014)), 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). Several other models of production frontiers (See Battese and Coelli, 1992; Khumbakar, 1990; Greene, 2005) can be found in the literature. They have been applied alternatively to our data to improve the robustness of our analysis, but their results are not reported here.

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 technical efficiency $\omega_{it} \in (0,1]$:

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

Where x_i is a Kx1 vector of inputs, β a Kx1 vector of parameters to be estimated. The technical efficiency can be considered as time-varying (TE_{it}) or time-invariant (TE_i). Both alternatives were applied to our data, but the results presented use a time-varying technical efficiency.

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

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

where

v_{it} 's correspond to the usual error term; they are assumed to be independent and identically distributed $N(0, \sigma_v^2)$ random errors which captures random variation in output due to factors beyond the control of producers;

$u_{it}'s$ are assumed to be independent and identically distributed non-negative truncations of the $N(\mu, \sigma^2)$ distribution. The condition $u_{it} \geq 0$ ensures that all observations lie on or beneath the production frontier.

Observe that u_{it} are non-negative region-specific effects associated with technical inefficiency.

Applying log transformation to equation (2) we get

$$ln y_{it} = ln f(x_{it};\ \beta) + v_{it} - u_{it} \qquad (3)$$

Note that, following Battese and Coelli (1995), we can specify a conditional mean model for u_{it} as

$$u_{it} = z_{it}\delta + W_{it}\ , \qquad (4)$$

where:

z_{it} is a Jx1 vector of explanatory variables; this vector includes the dummy for existence of water markets in the considered NRM region, climatic variables (potential evapotranspiration, Mean temperature, a measure of annual temperature differentials, Rainfall) and other variables (location within the Murray Darling Basin, time dummies and total irrigated area).
W_{it} is defined by the truncation of the normal distribution with zero mean and variance σ^2, such that $W_{it} \geq -z_{it}\delta$ (see Battese and Coelli, 1995 for details).

Thus, we simultaneously estimate the technical 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 technical inefficiency. Note that we are especially interested in the sign of our market variable's parameter in this regard.

In this model, the technical 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 technical efficiency $TE_{it} = \exp(-u_{it})$ 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 used in this paper. First, we used a Cobb-Douglas function, i.e.:

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

A more general function (Translog) can be applied, i.e.:

$$\ln f(x_{it}, \beta) = \beta_1 \ln AREA_{it} + \beta_2 \ln Wateruse_{it}$$
$$+\frac{1}{2}\beta_3(\ln AREA_{it})^2 + \frac{1}{2}\beta_4(\ln Wateruse_{it})^2 + \frac{1}{2}\beta_5 \ln AREA_{it} \ln Wateruse_{it}$$

Endogeneity issues

It should be noted that the problem of endogenous regressors may arise with the specification above. This issue is especially related to the presence of a water market. In this respect, we think that the presence of a water market can be affected by the level of agricultural production, political decisions made by the regulator and other factors that are not included in the model. Omitted variables include other production inputs such as labor and physical investment that are not observed from the data. Consequently, the estimation strategy should properly take the endogeneity of $Market_i$ into account.

Alongside the regressors included in the model, we believe two indicators can be used to instrument our Market variable. The total irrigated area within a region increases the pressure on water resources demand and thus the probability of existence of a water market. Moreover, historically, the Murray-Darling basin hosted the first water markets in Australia and has developed an extended juridical framework for the use of water markets. Its markets became the most intensively used markets in the country (see section Context). The affiliation to the MDB is therefore strongly related with the presence of a water market.

We adopt the control function approach (Woolridge, 2014) to estimate the model. We first performed a probit regression of our market variable *Market* on the set of explanatory variables w, which includes z, as well as MDB_i and $AREATirrig_{it}$ as two excluded instruments. We then computed 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, $\lambda(.) = \phi(.)/\Phi(.)$. Finally, we simultaneously estimate the production frontier model in (3) and (4) as explained above, but with an additional regressor corresponding to the estimated generalized residuals $\hat{g}r_i$.

Results

The frontier's results obtained concerning the grape production sector appear next:

	Grape Production			
	2007-2013		2009-2013	
	CD	TL	CD	TL
Frontier				
Water use	0.485***	0.484***	0.543***	0.552***
	(8.63)	(3.74)	(9.47)	(5.23)
Agricultural area	0.465***	1.092***	0.406***	1.101***
	(7.84)	(5.44)	(5.99)	(5.16)
Water use (squared)		0.0897**		0.0947**
		(3.12)		(3.05)
Agricultural area (squared)		0.0349		0.0335
		(0.84)		(0.69)
Interaction		-0.171*		-0.180**
		(-2.57)		(-2.59)
_cons	9.503***	7.823***	9.212***	7.814***
	(21.66)	(14.56)	(21.89)	(27.19)
N	246	246	187	187

t statistics in parentheses
* p<0.05, ** p<0.01, *** p<0.001

The classical components of our production function are behaving as expected: water use and the cultivated surface both have a significant positive impact on grape production.

Regarding technical efficiency, we generated mean regional TE scores through $E\{\exp(-u_{it})\}$. The 5 highest and 5 lowest scores appear in the following table:

NRM region	State	Grape Production	Mean temperature	PE	Market	Mean TE
Border Rivers-Gwydir	NSW	29616,43146	18,31785714	1644,63235	1	0,0492106
Kangaroo Island	SA	40069,54633	15,90555556	874,850867	0	0,16737446
Namoi	NSW	185125,9427	18,91944444	1768,79461	1	0,17415152
Hawkesbury-Nepean	NSW	41395,81849	14,76296296	1181,38426	0	0,18557364
Southern Rivers	NSW	82785,88162	15,04333333	1001,79342	0	0,21127956
.	.	.	.	.	.	.
South West	WA	59720048,46	16,82013889	1205,55513	1	0,71157246
Western	NSW	451629,9952	21,47083333	1630,235	1	0,71282673
Swan	WA	7399651,189	19,19404762	1454,51094	1	0,71906968
South (Tas.)	TAS	2281644,387	12,84444444	697,025852	1	0,73054952
North (Tas.)	TAS	7520110,877	13,07638889	750,392917	1	0,79695715

It appears that the highest Technical Efficiency (TE) scores are found in regions presenting a high level of grape production value. Although the two highest scores, found in Tasmanian regions, are subject to lower mean temperatures and potential evapotranspiration, it is difficult to notice a clear link between temperature and technical efficiency. However, in all the five regions presenting the highest TE scores, there are functioning water markets. In contrast, the lowest scoring regions in terms of technical efficiency tend to produce less grapes, and only 2 out of the five regions have functioning water markets. This suggests that water markets are associated with higher levels of technical efficiency, confirming the general expectations of the literature.

This hypothesis is confirmed by the conditional mean model for technical efficiency, estimated simultaneously with the stochastic production frontier:

	Technical Inefficiency in Grape production			
	2007-2013		2009-2013	
	CD	TL	CD	TL
Market	-1.184*	-1.135*	-1.645	-0.856*
	(-2.11)	(-2.00)	(-1.17)	(-2.08)
Potential evapotranspiration	-0.162	0.0896	-0.0966	0.303
	(-0.48)	(0.31)	(-0.17)	(1.19)
Rainfall	1.293*	1.032	1.529	0.783
	(2.22)	(1.83)	(1.37)	(1.91)
MDB	1.117**	1.039**	1.589	0.898***
	(2.77)	(3.02)	(1.46)	(3.83)
Generalized residual	0.162	0.195	0.253	0.0756
	(0.60)	(0.85)	(0.43)	(0.34)
Year 2007	-1.685*	-1.097*		
	(-2.00)	(-2.24)		
Year 2008	-0.279	-0.137		
	(-0.95)	(-0.58)		
Year 2009	-0.774	-0.494	-1.338	-0.431
	(-1.80)	(-1.67)	(-1.10)	(-1.83)
Year 2010	-0.891*	-0.620*	-1.310	-0.546*
	(-2.30)	(-2.04)	(-1.35)	(-2.26)
Year 2011	-1.004*	-0.704*	-1.608	-0.621**
	(-2.25)	(-2.27)	(-1.23)	(-2.78)
Year 2012	-0.208	-0.162	-0.373	-0.174
	(-0.83)	(-0.81)	(-0.84)	(-0.90)
_cons	0.986	1.182*	0.432	1.193*
	(1.62)	(2.10)	(0.38)	(2.56)
Usigma				
_cons	-0.686	-0.623*	-0.493	-0.406**
	(-1.48)	(-2.11)	(-0.63)	(-2.74)
Vsigma				
_cons	-1.325**	-2.172***	-0.982**	-14.56
	(-3.16)	(-3.60)	(-3.06)	(-0.88)
N	246	246	187	187

t statistics in parentheses
* p<0.05, ** p<0.01, *** p<0.001

t statis
* p<0.05,

Our main result is related to the Market variable, denoting the existence of water markets in a given region. The Market variable has a negative, significant impact on technical inefficiency, particularly when we include years of drought (2007 and 2008). Besides, the sign of the year dummies parameter suggest a historical tendancy towards less technical efficiency, as these parameters compare the obtained technical efficiency scores with those of the reference year (2013). A potential explanation for this phenomenon resides in the climatic conditions in the early years of our sample (2007 and 2008): the Millenium Drought that hit Australia, with effects lasting until 2010 in certain areas, occasioned high levels of economic pressure on farmers, and therefore could have provided clear incentives for farmers to reduce their inputs use.

Beyond the impact of our market variable, the impact of rainfall on agricultural production is, most of the time, insignificant. Rainfall's impact on agricultural productivity in the grape sector has been commented in the literature (see Webb, 2006) as having two contradictory impacts: it is generally expected to have a negative influence on agricultural yield in the case of grapes as it increases disease risk for the crop, while it increases the amount of water available to grapevines, thus favoring their growth. Our result is inconclusive in this matter, although there is slight evidence towards a negative impact when we take years of drought into account.

We applied a similar methodology to data related to the Australian agricultural sector as a whole; we find similar results, that can be found in Appendix 1.

Our results, however, must be interpreted carefully. Important limits have to be stated. First, as the available data was limited, we did not account for the intensity of market activity: instead, we measured the existence of water markets in a given region. Second, we measured market impacts at an aggregated NRM level: it would be interesting to conduct the analysis at a farm level, if enough data could be available. Nevertheless, our result concerning grape production confirms the expectations formulated by the literature on water market impacts, as well as the predictions made by general equilibrium modelling (Peterson et al., 2005). Bjornlund (1999), in his empirical study of two specific areas presenting water markets in the Murray-Darling Basin, noticed that water was sold to more efficient farmers in terms of water use and value generated. Our findings confirm that these impacts can be noticed at a more aggregated level.

Robustness tests

In order to improve the validity of our results, different robustness and sensitivity tests were conducted.

As the data coming from the Australian Bureau of Statistics' database is collected by random sampling, they are subject to potential errors. The corresponding error risk is specified in the data published by the ABS. The data relating to grape production is affected, but the errors in the data on total agricultural production are very low. As such errors might undermine the validity of our results related to grape production, we conducted the main regressions while excluding observations subject to a standard error superior to 25% of the observation's value (Appendix 2). We find no difference in the results.

In order to justify the additional use of a translog production function, the null hypothesis that all quadratic and interaction terms are equal to zero was tested against the data, indivudally and collectively. The joint null hypothesis is rejected, along with the individual null hypothesis related to water use and the interaction term. The only squared term whose coefficient does not differ significantly from zero is agricultural surface. This suggests that the use of a translog specification is justified (Appendix 3).

Finally, we tested the potential weakness of our instruments. We ran a classic panel data regression, using the instrumental variables methodology, and computed the Cragg Donald. We found no weak instrument according to Stock and Yogo's critical values (Stock and Yogo, 2005. Results for this test can be found in Appendix 4.

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Reports used in the constitution of the data (Source: Australian Bureau of Statistics):

For each year from 2007-08 to 2013-14 included:

‘Agricultural Commodities’

‘Value of Agricultural Commodities Produced’

‘Water Use on Australian Farms’

Appendix 1: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Grape Production value	282	2.65e+07	6.15e+07	0	4.44e+08
Total Production value	282	8.62e+08	4.83e+08	4335243	2.47e+09
Agricultural area (Grapes)	282	3963.171	6927.159	0	31938
Agricultural area (Total)	282	6896819	1.33e+07	7919	7.42e+07
Total irrigated area	282	65823.16	387288.5	.3	6489766
Water used (Grapes)	282	11413.96	29337.72	0	156835.6
Water used (Total)	282	171718.6	239063.8	1.3	1499934
Potential Evapotranspiration	282	1356.713	323.9348	598.5183	2089.178
Mean temperature	282	17.66553	3.52758	12.16991	26.89107
Spread temperature	282	25.40915	4.462982	15.35714	34.98
Location within the MDB	282	.3404255	.4746947	0	1
Existence of a water market	282	.6808511	.4669756	0	1

Appendix 2: Results from data on the agricultural sector

Frontier:

	Agricultural production			
	2007-2013		2009-2013	
	CD	TL	CD	TL
Frontier				
Water use	-0.00414	-0.215	0.00959	-0.160
	(-0.25)	(-1.31)	(0.54)	(-0.92)
Agricultural area	0.0821**	2.508***	0.0945**	2.419***
	(2.61)	(16.25)	(2.77)	(14.19)
Water use (squared)		0.0150*		0.0123
		(2.05)		(1.55)
Agricultural area (squared)		-0.0823***		-0.0798***
		(-12.00)		(-10.87)
Interaction		-0.00690		-0.00579
		(-0.72)		(-0.58)
_cons	19.93***	3.668***	19.59***	3.973**
	(38.28)	(3.30)	(35.90)	(3.22)
N	361	361	261	261

Determinants of technical inefficiency:

	Technical Inefficiency			
	2007-2013		2009-2013	
	CD	TL	CD	TL
Market	-26.16*	-38.88	-20.55*	-38.71
	(-2.16)	(-1.78)	(-2.08)	(-1.21)
Potential evapotranspiration	0.884	-0.901	0.956	-1.424
	(0.71)	(-0.39)	(0.82)	(-0.54)
Rainfall	6.394*	10.26	5.171*	10.34
	(2.13)	(1.79)	(2.07)	(1.25)
MDB	8.402	13.86	6.235	14.75
	(1.82)	(1.61)	(1.62)	(1.10)
Generalized residual	16.76*	24.90	12.99*	24.55
	(2.15)	(1.79)	(2.05)	(1.21)
Year2007	0.411	-0.828		
	(0.28)	(-0.30)		
Year2008	0.176	-1.094		
	(0.12)	(-0.38)		
Year2009	0.257	-0.618	0.230	0.516
	(0.18)	(-0.23)	(0.20)	(0.22)
Year2010	-1.413	-2.772	-1.187	-2.002
	(-0.89)	(-0.87)	(-0.91)	(-0.74)
Year2011	-0.535	-2.087	-0.463	-1.062
	(-0.36)	(-0.69)	(-0.39)	(-0.45)
Year2012	0.459	-2.288	0.323	-0.633
	(0.31)	(-0.67)	(0.27)	(-0.26)
_cons	0.0175	-0.301	0.0101	0.650
	(0.01)	(-0.07)	(0.00)	(0.16)
Usigma				
_cons	1.832***	2.271***	1.576**	2.092*
	(3.79)	(3.78)	(3.22)	(2.51)
Vsigma				
_cons	-3.149***	-3.012***	-3.323***	-3.044***
	(-11.84)	(-13.68)	(-9.40)	(-11.50)
N	361	361	261	261

t statistics in parentheses
* p<0.05, ** p<0.01, *** p<0.001

Appendix 3: Robustess test 1 : excluding observation subject to an ABS error level >1

Frontier:

	Grape Production 2007-2013	
	CD	**TL**
Frontier		
Water use	0.722***	0.905***
	(11.73)	(5.40)
Agricultural area	0.187**	0.634*
	(2.68)	(2.44)
Water use (squared)		0.0728
		(1.89)
Agricultural area (squared)		0.0578
		(1.17)
Interaction		-0.173*
		(-2.06)
_cons	11.06	8.923
	(0.19)	(0.43)
N	143	143

Determinants of technical inefficiency:

	Technical Inefficiency 2007-2013	
	CD	TL
Market	-0.695*	-0.743*
	(-1.97)	(-2.19)
Potential evapotranspiration	0.653**	0.732**
	(2.86)	(3.19)
Rainfall	0.639**	0.757**
	(2.64)	(3.23)
MDB	0.664***	0.695***
	(3.40)	(3.53)
Generalized residual	0.110	0.162
	(0.54)	(0.83)
Year 2007	-0.211	-0.156
	(-1.26)	(-0.97)
Year 2008	0.0554	0.103
	(0.31)	(0.60)
Year 2009	0.107	0.143
	(0.54)	(0.76)
Year 2010	0.0806	0.111
	(0.44)	(0.64)
Year 2011	0.0626	0.0565
	(0.37)	(0.35)
Year 2012	0.247	0.211
	(1.48)	(1.32)
_cons	0.979	0.939
	(0.02)	(0.04)
Usigma		
_cons	-3.313	-2.834
	(-0.17)	(-0.15)
Vsigma		
_cons	-1.501	-1.747
	(-0.48)	(-0.28)
N	143	143

Appendix 4: Justification of a translog specification

Test 1
H0 : The coefficient of Water use (squared) is equal to zero.
chi2 (1) = 16.02
Prob > chi2 = 0.0583
Test 2
H0 : The coefficient of Agricultural surface (squared) is equal to zero.
chi2(1) = 1.37
Prob > chi2 = 0.2420
Test 3
H0 : The coefficient of the interaction term is equal to zero.
chi2(1) = 4.25
Prob > chi2 = 0.0394
Test4: Joint hypothesis
H0: All squared and interaction terms are equal to zero
chi2(3) = 16.02
Prob > chi2 = 0.0011

Appendix 5: testing for weakness in our instruments

The results of the weak identification test, using Cragg Donald statistics and critical values from Stock and Yogo (2005), appear in the following table:

Weak identification test

Null Hypothesis	H0: instrumented variable weakly identified
Cragg Donald statistic	23.46
Critical value	19.93
H0 rejected?	YES