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Economic effects of climate change in the Murray–Darling Basin, Australia

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ABSTRACT

This study uses a hydro-economic model to examine the role of water trading, and the economic impacts of climate change and reduced surface water availability in the Murray–Darling Basin. The results show that losses to irrigated agriculture under a median climate change scenario are modest, but under a 'modified 2030 dry extreme scenario' there would be substantial reductions in water use, irrigated land use and profits. Nevertheless, the Basin-wide proportional economic impacts would be less than the percentage decline in water use. A comparison of model results with and without inter-regional water trade shows that inter-regional water trade in periods of much reduced water availability mitigates the on-farm impacts of climate change. Given that agricultural production in the Basin is likely to be affected by climate change, the development of drought-tolerant crops and cultivars along with learning and extension of best farming practices to reduced water use could also assist irrigated agriculture adapt to climate change within the Basin.

1. Introduction

The Murray–Darling Basin (MDB) is Australia's largest and most important agricultural production area. It produces some $15 billion worth of agricultural products annually and accounts for about 40% of Australia's total agricultural production (Murray–Darling Basin Authority, 2010). The MDB is also a major centre for Australian economic activity: over 2 million people live and more than 900,000 people are employed in the Basin (Murray–Darling Basin Authority, 2010).

From 2002 to 2009, annual rainfall in the MDB was significantly lower than the long-term average. As a result, from 2005/06 to 2007/08, irrigated land use in the MDB fell from 1654,000 ha to 958,000 ha, a decline of 42%. From 2001 to 2006 the number of farmers and farm managers also declined from 73,000 to 67,000, a fall of 7.4% (Murray–Darling Basin Authority, 2010). These changes provide an indication of the possible impacts of reduced water availability may occur with climate change (CSIRO, 2008).

There have been relatively few climate change studies within the MDB, especially at the regional scale. To better understand water availability in the MDB under climate change, the Australian government in 2006 commissioned the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to study future rainfall and runoff in the MDB. In 2008, CSIRO released its predictions for the period 2008–2030 (CSIRO, 2008) and projected that surface water availability across the entire MDB was more likely to decline than to increase. To focus on water management at the regional scale, CSIRO divided the MDB into 18 regions and provided one of the world's most complete hydrological studies of a large Basin.

A comprehensive review of hydro-economic models in general – including concepts, design, applications, and future prospects – is given by Harou et al. (2009). Similar models have been widely applied in climate change studies. For instance, Guan and Hubacek (2008) constructed a hydro-economic model to investigate water use in North China.

In the MDB, some researchers (Connor et al., 2009; Goesch et al., 2009; Adamson et al., 2009) have modelled the economic impact of reduced water supply in the MDB due to climate change. None of these studies, however, use both the regional boundaries developed by CSIRO in its climate change models and the full range of possible scenarios in 2030 — in particular the worst-case scenarios. Our study addresses these limitations and focuses on economic impacts at the regional scale. Previous hydrological and economic studies are reviewed in Sections 2.1 and 2.2, while discussions about the differences between this study and previous work are provided in Section 2.3.

To overcome the limitations of existing studies, an integrated irrigated agriculture water model (IIAWM) is developed and used to assess the effects of climate change in 2030 under a range of scenarios. A key contribution of our study is that the IIAWM employs the regional boundaries and water use forecasts from the CSIRO Sustainable Yields Project. To study the effects of water trading, hydrologic limitations to trading have been incorporated into the model, and trading between individual regions is simulated. The model quantifies the economic impact of climate change on the

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irrigation-based industries of the MDB. In particular, it evaluates three climate scenarios in 2030 and provides regional and Basin-wide results, with and without water trading, in terms of: water use, profit, and land-use.

Our research claims three contributions. First, it provides assessments of economic impacts at a regional scale. Thus, it avoids the regional boundary inconsistencies that have become evident between existing models and that impede regional policy developments. Second, because a wider range of climate change scenarios are examined, the actual risks of climate change can be better understood, especially under the driest climate change scenarios. Policy makers can, therefore, consider the worst climate change possibilities, rather than being limited to moderate climate change scenarios or climate change over a restricted part of the MDB. Finally, we quantify the extent that water trading at a Basin scale can play in the adaptation process.

The rest of this paper is structured as follows: Section 2 provides an overview of existing water studies in the MDB that is followed by considerations of a theoretical framework and sources of data in Section 3. Section 4 presents results and in Section 5 we discuss their implications. Finally, Section 6 sets out a conclusion and some policy implications.

2. Previous studies in the MDB

This section reviews existing studies, assesses their limitations, and raises important issues in modelling climate change effects. Based on objectives and features, existing studies fall into two categories: hydrologic research and economic research.

Most studies suggest that MDB-wide water supply will be reduced by climate change, especially in the Southern part of the Basin. Comprehensive evaluations of these physical impacts on irrigated agriculture are limited (Connor et al., 2009; Goesch et al., 2009). However, until now, there has been no hydro-economic study that has examined the extreme climate change scenarios developed by CSIRO in its Sustainable Yields Project.

2.1. Hydrological research

Hydrological research in the Basin has sought to estimate future runoff and water supply changes caused by reduced rainfall. The first step in the process is to agree on a future climate projection and then determine what that may mean for surface water supplies. The most common approach is to start with global climate models (GCMs) that provide a spectrum of climate change data.

The most comprehensive climate change study to date was carried out as part of by CSIRO's Sustainable Yields Project (CSIRO, 2008). This work was initiated in 2006 when the Australian government sought scientific evidence to underpin a sustainable water plan for the entire MDB. The Australian government commissioned CSIRO to study future water availability and use in the basin. In terms of model accuracy and data quality, CSIRO evaluated and applied the best available models currently then available. For climate projection, CSIRO simulated different climate change scenarios by using 15 various GCM models. For rainfall–surface runoff, models such as IQQM, REALM, MSM-BigMod, WaterCress, and SMHS were used. The output of the CSIRO work provides predictions of future water availability and use in the MDB from 2008 until 2030.

2.2. Economic research

Most of the economic research in the MDB has adopted a hydro-economic modelling approach similar to other studies outside the MDB (Guan and Hubacek, 2008; Harou et al., 2009; Berrittella et al., 2007). These studies vary in the choice of the selected climate change scenarios, the regional boundaries, and the model parameters.

Concentrating on the Lower Murray, a small proportion of the Basin area, Connor et al. (2009) modelled the economic impact of climate change on irrigated agriculture in the region. The authors assessed the effects of three scenarios: (1) a mild climate change with a 13% reduction in inflows throughout the MDB; (2) a moderate climate change with a 38% reduction; and (3) severe climate change with a 63% reduction. They found that profit reductions would be much less than the corresponding declines in inflows, given an unrestricted water market in the region. For example, with moderate climate change and unrestricted water trading, net returns in Victorian and South Australian agriculture declined by 5% and 11% respectively.

At the basin scale, Goesch et al. (2009) used the ABARE water model and the median climate change scenario from CSIRO's Sustainable Yields Project to assess the economic effects of climate change in the MDB. They predicated that overall diversions would fall by about 4%, while irrigators' income would drop by about 1%. The Goesch et al. (2009) model most resembles the IIAWM model used in this paper. However, Goesch et al. (2009) used only one of the four climate change scenarios developed by CSIRO. Thus, Goesch et al. (2009) did not evaluate the economic effects of severe climate change. By contrast, our study evaluates the economic impacts of all climate change scenarios from the CSIRO study.

Adamson et al. (2009) assessed the effects of climate change on irrigated agriculture, in this case using the different climate scenarios developed by Jones et al. (2007) for 2030. The authors found that, using their best estimates, the social value in the MDB will decline by at least \$250 million/year (about 5% of the total) and possibly to \$800 million/year, or about 16% of the total. Since the climate change forecasts from Jones et al. (2007) cannot achieve the same level of detail and accuracy of the CSIRO Sustainable Yields Project, the CSIRO data are considered the most appropriate climate change data for the MDB and are used here. Hydro-economic studies have also been undertaken by Grafton and Jiang (2011) and by Mallawaarachchi et al. (2010) to investigate changes in water availability due to changes in Basin water planning.

2.3. Previous research limitations and important issues in modelling

2.3.1. Regional boundaries

Consideration of regional boundaries is essential in water studies and in policy making. Various government agencies and researchers, however, have developed their own ways of defining regional boundaries. Unfortunately, differences in the regional boundaries create an obstacle when comparing alternative MDB models. Moreover, they make it very difficult for policy makers to utilise research findings and apply them to specific regions.

In 2008, CSIRO introduced a comprehensive catchment-based way of defining regional boundaries in the MDB, dividing the region into 18 different catchments. Except the study undertaken by the Goesch et al. (2009), most of the previous studies use the different regional numbers and boundaries such as the 19 regions in the study by Mallawaarachchi et al. (2010). Given that most of the modelling research was undertaken prior to the CSIRO Sustainable Yields Project, policy makers have not been able to extract good regional information from these models. To address this challenge, we use the regional number and boundaries from the CSIRO Sustainable Yields Project.

2.3.2. Climate change scenario

The CSIRO Sustainable Yields Project (CSIRO, 2008) represents the best available science about the effects of possible climate change in the MDB. However, because there is uncertainty in global warming projections and in predictions of rainfall, the ap-

Table 1
Historical climate and climate-change scenarios from the CSIRO Sustainable Yields Project (CSIRO, 2008).

Climate scenario	Rainfall (mm)	Rainfall (% change from historical)	Runoff (mm)	Runoff (% change from historical)
Historical (1985–2006) climate	457	0	27.3	0
Recent (1997–2006) climate	440	−4	21.7	−21
Future (2030) climate – median	444	−3	24.7	−9
Future (2030) climate – dry extreme	396	−13	18.3	−33
Future (2030) climate – wet extreme	495	8	31.7	16

proach taken by CSIRO was to provide a range of climate change scenarios from modest to severe. In particular, the CSIRO project reviewed water resources over two historical periods and applied three climate change scenarios (Table 1).

In its review of historical climate, CSIRO examined the long-term historical climate (1895–2006) as well as the last 10-year drought (1997–2006), defined as follows:

- The long-term historical climate (1895–2006) was represented by 112 years of daily climate data. This data set served as the baseline for studying a range of climate and development scenarios.
- The second point of reference was the climate data from the drought years 1997–2006. This data set was used to evaluate the consequences of a long-term severe drought in the MDB.

To project the possible effects of future climate change, CSIRO also developed three climate change scenarios for the year 2030. They were called the median 2030 climate, the dry extreme 2030 climate, and the wet extreme 2030 climate. They were developed using 15 global climate models (GCMs).

- The median, or best estimate, 2030 climate is the median result from the 15 GCMs. It is CSIRO's 'most likely' climate for the year 2030.
- The dry extreme 2030 climate is the second-driest result from the high global warming scenario.
- The wet extreme 2030 climate is the second-wettest result from the high global warming scenario.

Ideally, policy makers would like to know the consequences of all climate change scenarios. Goesch et al. (2009) examined the median climate change scenario and found that irrigators' average income would decrease by 1%, while the 2030 surface runoff would be reduced by 9%. However, between 1999 and 2009, water availability in the MDB fell by 40% relative to the long-term average (Murray–Darling Basin Authority, 2010). This reduction in the recent drought far exceeds the 9% reduction reflected in the median climate change scenario developed by CSIRO. Without evaluating the effects of severe climate change, neither farmers nor policy makers are able to adequately plan and adapt to a possible future with much less water availability.

3. Models and results

3.1. Hydro-economic model

Any land use in each catchment must satisfy two constraints: a catchment water availability constraint and a land use constraint. The catchment water availability constraint means that the irrigation water use in a catchment cannot be more than the water available in this catchment. The land use constraint means that, without the additional irrigation establishment investments, the land use in any catchments cannot be expanded beyond existing limit.

To consider climate change simulations, the IIAWM model uses as inputs the water availability from the past, and also CSIRO 2030 projections along with existing water infrastructure and land constraints. For each climate change scenario, the water availability and water use target for each region in IIAWM was replaced with the predicted data from CSIRO (2008).

Without additional investments in irrigation establishment costs, irrigated land use cannot be expanded. Thus, without additional investments, simulated land use should be limited by the existing irrigation infrastructures or long-term irrigated land use. In the IIAWM model, the available irrigated land in each region is limited by a land use constraint that represents the long-term irrigated land use. However, land constraints follow the constraints set out in the 2000–2001 basin land use data, but because the 2000–2001 water use was less than the long-term basin average, it is necessary to increase the water demand to match long-term water use. In other words, the IIAWM land constraint is scaled to match long-term land and water use in the MDB.

Land use is the key variable that drives the results of the model because other variables, such as water use and economic returns, depend on the land use. After the land use decision is made, water use and economic returns are calculated according to the land use. To link the water use with land use, irrigation rates are used to determinate the water use for each crop. Similarly, to link the economic returns with the land use, gross value rates and cost rates are used to determine the economic returns.

In its economic component, IIAWM uses data from the Australian Bureau of Statistics (2008) and Bryan and Marvanek (2004) to model the seven largest uses of water diverted by irrigators: (1) pasture and hay; (2) rice; (3) cotton; (4) cereals (excluding rice); (5) grapes; (6) fruit (excluding grapes); and (7) vegetables. This study focuses only on irrigated industries.

In its hydrological component, IIAWM represents the MDB river system as a network and each region is a node in the network. The model takes into account physical constraints in trade that limit transfers of water from some catchments (such as in the Paroo, Wimmera, and Lachlan Rivers), but initially assumes no market constraints on water trade. Water use targets can be allocated to each region or to the basin as a whole. All hydrological data are from CSIRO (2008). Water use in farms represents water diversion from channels. Due to a lack of data about conveyance losses from the river channel to farms, these losses are not considered. At the regional level, however, some researchers have found that conveyance losses in the Murrumbidgee region, located within the MDB, can be as high as 29% (Qureshi et al., 2010). Similarly, as a lack of data about the spatial distribution of various water licences, water license types are not considered in this study.

Water balances in each region are simulated as if each region or catchment receives inflows from upstream (if they have an upstream region). After accounting for water consumption and losses, the end-of-system flows are transferred to the next downstream region. Thus, for any catchment or region i, the end-of-system flows are calculated as:

$$F_e = F_{in} + F_r - W_u - W_e - W_l \quad (1)$$

where F_e is the end-of-catchment flow that benefits the next downstream catchment or region, F_{in} is the combined inflows from the upstream regions (if region i has an upstream catchment), F_r is the water inflow generated by region i, and W_u is the net water used for diversions in region i. In any catchment i, W_e represents environmental flows in region i that remain in the catchment, and W_l are evaporative and conveyance losses. W_u is the total water demand from all seven irrigated agriculture activities defined by following equation:

$$W_u = \sum_{j=1}^{7} L_j \times R_j \tag{2}$$

where L_j is the irrigated land area for activity j in region i and R_j is the irrigation water rate in ML/ha for activity j in 2000/01 (Australian Bureau of Statistics, 2008, p. 74). The amount of water used in region i is constrained to be equal to or less than upstream inflows plus inflows from the region itself, less any water allocated for environmental flows.

The objective is to maximise Eq. (3) subject to irrigated land area constraints (Eq. (4)) and water diversion constraints (Eq. (5)).

$$\text{Maximise Net Profits} = \sum_{i=1}^{18} \sum_{j=1}^{7} \Pi_{ij} \times L_{ij} \tag{3}$$

$$L_{ij} \leqslant TL_{ij} \tag{4}$$

$$W_{ij} \leqslant TW_{ij} \tag{5}$$

where Π_{ij} is the net profit to irrigation activity j in catchment i; L_{ij} is the land area devoted to activity j in catchment i; TL_{ij} is the total irrigated land available to activity j in catchment i; W_{ij} is the water use of activity j in catchment i; and TW_{ij} is the total available water to activity j in catchment i.

The model calculates the net profit from all irrigation activities in region i as per Eq. (6):

$$\Pi_i = \sum_{j=1}^{7} L_j \times E_j - \sum_{j=1}^{7} V_j - \sum_{j=1}^{7} FC_j \tag{6}$$

where E_j is the gross value rate for activity j in region i; Gross value rate equals the price of the product multiplied by the yield (quantity of production) per hectare. V_j are the variable costs, including quantity-dependent costs, area-dependent costs, and water costs ($/ha). Quantity dependant variable costs are costs that vary with the quantity of output produced, such as the tonnes of barley. Typical quantity dependent costs include harvest costs, storage costs, handling costs, and product treatment costs.

The quantity dependant variable costs ($/ha) equals to the quantity dependant variable cost rates ($/tonne) multiplied by the yield (quantity of production) per hectare. Area dependent variable costs include costs that vary with the area of production such as the cost of seed or fertiliser, or harvesting costs.

Area dependent variable costs are represented as $/ha. Water costs equal the typical water requirements in ML/ha of each land use derived from irrigation benchmarking studies multiplied by the price of water in $/ML. The water costs units are $/ha. FC_j are fixed costs and fixed labour costs, including operating costs and depreciation. Fixed operating costs include land rates, accountant fees, costs for energy, waste disposal, maintenance, insurance and administrative overheads. Fixed depreciation costs include depreciation of farm machinery such as tractors, harvesters and sprayers, and infrastructure such as irrigation pipes and fences. Fixed labour costs include the total cost per hectare of labour required in the production of each crop.

3.2. Climate change scenarios

We examine one historical climate scenario and three climate change scenarios that are derived from the CSIRO Sustainable Yields Project (CSIRO, 2008). These include:

(1) The 'historical scenario' based on a continuation of the long-term (1895–2006) average for rainfall and runoff across the MDB.
(2) A 'median 2030 scenario' based upon the median global warming scenario and associated rainfall and runoff described in the CSIRO report on Water Availability in the Murray–Darling Basin.
(3) A 'recent drought scenario' based upon the actual climate of the MDB in the period 1997–2006 (this includes 15% less rainfall and 50% less runoff in the southern MDB when compared with the long-term average), and
(4) A 'modified dry extreme 2030 scenario' based upon the water availability of the driest year in the dry extreme 2030 scenario.

Scenarios (1–3) are derived directly from the CSIRO (2008) Sustainable Yields Project and scenario (4) is extracted from the CSIRO data as the driest year in the 2030 dry extreme scenario modelled by CSIRO. The numbers for all the scenarios come directly from the main CSIRO (2008) report, or from separate water availability reports referenced in CSIRO (2008).

3.3. Simulations

The two key goals of the study are to examine the effects of severe climate change and to investigate whether water trading can significantly offset these effects. Climate change was simulated in two steps. In the first, we use historical climate data to create a calibration that provides a baseline for the other simulations. We then simulate the climate change scenarios and compare their differences in percentage terms relative to the baseline results. In the second step we repeat the process, but allow for water trading between regions and then calculate the differences to assess the effects of water trade.

4. Results

The results are set out in Tables 2–7, where we show, for each of the 18 regions, changes in water availability, profits, and irrigated land use. Each column shows the difference between three key scenarios and the long-term historical average. Tables 2–4 show calculations based on CSIRO's predictions of water use and assuming *no* inter-regional water trade, whereas Tables 5–7 give comparable figures which allows for water trading between regions. Note that total water use in Tables 5–7 is the same as in Tables 2–4, although water use in each region changes as a result of water trading.

A consistent result across all the tables is that losses under the median climate change scenario are modest. Total water use in the median scenario is only slightly less than in the historical scenario. By way of contrast, in the recent drought, and in the modified 2030 dry extreme scenario, a number of regions appeared to suffer substantial losses. The possible losses under the median 2030 scenario appear to be unaffected by water trading. However, with the modified 2030 dry extreme scenarios, water trading does reduce the reductions in irrigated profits by as much as 7%.

4.1. Water use

To investigate water use, regional water use figures are utilised as reported by CSIRO (Table 2). The numbers do not include inter-regional water trading. Water trading, however, allows for trans-

Table 2
Change in irrigated surface water extractions (%) in the Murray–Darling Basin compared to the long-term historical average – *without inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Barwon–Darling	−2	−4	−91
Border rivers	−2	0	−87
Campaspe	−5	−26	−87
Condamine–Balonne	−4	−2	−89
Eastern Mt Lofty ranges	0	0	−38
Goulburn–Broken	−6	−24	−95
Gwydir	−9	0	−95
Lachlan	−8	−9	−94
Loddon–Avoca	−6	−28	−96
Macquarie–Castlereagh	−4	−4	−94
Moonie	−6	0	−100
Murray	−4	−14	−76
Murrumbidgee	−2	−18	−67
Namoi	0	−28	−88
Ovens	0	−4	−46
Paroo	0	0	0
Warrego	−4	NA	−82
Wimmera	−11	−44	−98
Total	−4	−13	−81

[a]NA = not available from CSIRO's Warrego water availability sustainable yields report.

Table 3
Profit change (%) in the Murray–Darling Basin under various climate change scenarios compared to the long-term historical average – *without inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Barwon–Darling	−2	−4	−83
Border rivers	−1	0	−58
Campaspe	−3	−22	−81
Condamine–Balonne	−1	0	−73
Eastern Mt Lofty ranges	0	0	−38
Goulburn–Broken	−3	−15	−78
Gwydir	−8	0	−90
Lachlan	−1	−1	−75
Loddon–Avoca	−4	−20	−76
Macquarie–Castlereagh	−3	−3	−74
Moonie	−5	0	−100
Murray	−1	−4	−34
Murrumbidgee	−1	−6	−27
Namoi	0	−22	−69
Ovens	0	−1	−33
Paroo	0	0	0
Warrego	−1	NA	−73
Wimmera	−2	−31	−96
Total	−1	−7	−51

[a]NA = not available from CSIRO's Warrego water availability sustainable yields report.

fers of water across regional boundaries, depending on demand, although the total Basin water use necessarily remains the same.

Table 5 shows the results of simulations after allowing for inter-regional water trade. As the bottom row shows, in the median 2030 scenario, total water use is reduced by 4%; in the recent drought scenario it is reduced by 13%; and in the modified dry extreme 2030 scenario it is reduced by 81%. A comparison of Tables 2 and 5 shows that water trading can ameliorate the impact of water shortages. For example, under the current water-sharing agreements, the largest reduction in water use under the recent drought scenario (Table 2, middle column) is the Wimmera region, with a 44% reduction. However, when inter-regional water trading is allowed, the Wimmera's shortfall is partly accommodated from other regions and the Wimmera reduces its surface water use by only 16%.

4.2. Profit change

Table 3 shows the change in profits (negative numbers mean a decrease) under various scenarios, but with no water trading, while Table 6 shows the change in profits when water trading is allowed. We find that water trading mitigates the impact of drought. In Table 3, bottom row, profits under the median 2030 scenario are reduced by only 1%, whereas under the recent drought scenario by 7%, and under the modified dry extreme 2030 scenario by 51%. When inter-regional water trade is permitted, profit reductions are *less*. Table 6 shows that, with the mitigation of inter-regional water trade, profit reductions fall in the recent drought by 5%, and in the dry extreme scenario by 44%.

The profit reductions are substantially smaller than the water use reductions. For example, the last two columns of Table 2 show a 13% and 81% water use reduction, whereas profits (the corresponding columns of Table 3) are reduced by only 7% and 51%. The reason for this outcome is that the least profitable irrigation activities are those eliminated first when water availability is reduced at the farm level and also at a catchment level given competitive water markets. With water trading both within and across catchments (Table 6), profit reductions are less overall because water can be allocated to its highest value use over multiple regions within the Basin. Compared to the historical climate scenario, with water trade, net profits decline by 44% under the modified dry extreme scenario. This profit reduction is less than the profit reduction without water trade (51%). However, the negative effects are not uniform across the MDB and some regions have very large reductions in net profits such as the Gwydir (96%) and the Campaspe (89%) in the dry extreme scenario with water trade (Table 6).

4.3. Land use change

As overall water availability declines in the Basin, farmers may be forced to transfer some irrigated land use to non-irrigated land use. There are two options for farmers: transfer irrigated land to dry land agriculture or to fallow land. Table 4 shows reductions in irrigated land use caused by climate change and Table 7 presents the same results, but with the mitigating effect of water trading included. In the latter case, under the median 2030 scenario, land use is reduced by 5%; under the recent drought scenario, by 10%; and under the modified dry extreme 2030 scenario, by 81%.

In general, reductions in irrigated land use follow reductions in water use throughout the MDB, although there are regional differences. There are two possible explanations for this trend. First, deficit irrigation is not considered in this study. Second, in our study, the water use is determined by land use. Thus, it is reasonable to believe that the land use reductions are similar to the water use reductions. For instance, the Condamine–Balonne (Table 7) incurs a 96% reduction in land use with water trade (90% without water trade, Table 4) in the modified dry extreme scenario. However, in terms of profits (Tables 3 and 6), there is a somewhat lower fall (79% with trade and 73% without trade). This happens because drought causes large reductions in low-valued irrigation crops whereas higher valued crops (such as vegetables, fruits, and grapes) are retained.

Table 4
Irrigated land use change (%) in the Murray–Darling Basin under various climate change scenarios compared to the long-term historical average – *without inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Barwon–Darling	2	−4	−90
Border rivers	−2	0	−86
Campaspe	−3	−25	−88
Condamine–Balonne	−8	−3	−90
Eastern Mt Lofty ranges	0	0	−38
Goulburn–Broken	−4	−23	−96
Gwydir	−9	0	−95
Lachlan	−12	−14	−94
Loddon–Avoca	−6	−28	−96
Macquarie–Castlereagh	−4	−6	−93
Moonie	−8	0	−100
Murray	−5	−9	−73
Murrumbidgee	−6	−27	−54
Namoi	0	−28	−87
Ovens	0	−5	−46
Paroo	0	0	0
Warrego	−3	NA	−80
Wimmera	−14	−44	−97
Total	−5	−15	−78

[a]NA = not available from CSIRO's Warrego water availability sustainable yields report.

Table 5
Change in irrigated surface water extractions (%) in the Murray–Darling Basin compared to the long-term historical average – *with inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Barwon–Darling	0	0	−99
Border rivers	0	0	−5
Campaspe	−16	−54	−98
Condamine–Balonne	0	0	−96
Eastern Mt Lofty ranges	0	0	−35
Goulburn–Broken	−1	−1	−90
Gwydir	−1	−1	−99
Lachlan	−15	−15	−82
Loddon–Avoca	−18	−50	−92
Macquarie–Castlereagh	−7	−7	−41
Moonie	−1	−1	−36
Murray	−5	−23	−82
Murrumbidgee	0	0	−84
Namoi	−9	−9	−97
Ovens	−1	−1	−43
Paroo	0	0	0
Warrego	0	0	−42
Wimmera	−1	−16	−17
Total	−4	−13	−81

5. Discussion

5.1. Water trading

If there were no water trade the water use reductions by catchment would generally follow those predicted by CSIRO in its water availability report. For instance, for the Murrumbidgee, we find a 2.4% reduction in water use in the median 2030 scenario (Table 2) and in the modified dry extreme 2030 scenario we find a 67% reduction in water use in the Murrumbidgee and the virtual elimination of irrigation in many regions (Table 2).

Table 6
Profit Change (%) in the Murray–Darling Basin under various climate change scenarios compared to the long-term historical average – *with inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Barwon–Darling	0	0	−94
Border rivers	0	0	−3
Campaspe	−15	−49	−89
Condamine–Balonne	0	0	−79
Eastern Mt Lofty ranges	0	0	−8
Goulburn–Broken	0	0	−59
Gwydir	0	0	−96
Lachlan	−2	−2	−39
Loddon–Avoca	−12	−34	−63
Macquarie–Castlereagh	−1	−1	−28
Moonie	0	0	−35
Murray	−1	−7	−38
Murrumbidgee	0	0	−41
Namoi	−2	−2	−83
Ovens	0	0	−10
Paroo	0	0	0
Warrego	0	0	−8
Wimmera	0	−3	−3
Total	−1	−5	−44

Water trading enables irrigators to adapt to climate change. A comparison of Tables 2 and 5 shows the region-by-region changes are different with and without water trade. This reflects differences in the net returns per ML of water across the seven irrigated crop activities and between the regions. It confirms the important role that water trading can have in droughts. For instance, in the recent drought scenario, water trade can ameliorate profit reductions by 2% (−5% in Table 6 compared to −7% in Table 3). In the modified dry extreme 2030 scenario, water trade can ameliorate the situation by 7% (−44% in Table 6 compared to −51% in Table 3). The greater the decline in water availability the greater is the benefit of water trading. For instance, in the median 2030 climate scenario, the water use was only reduced by 4% and profits were unchanged.

5.2. Policy implications

The results provide some possible policy implications and indicate that inter-regional water trading may assist with climate adaptation. In terms of the MDB, we find that inter-regional water trading is an important way to mitigate the losses associated with extreme climate change. Water markets help move water to where it is most valuable in terms of consumptive use and, therefore, help maintain the value of production when runoffs decline. In addition, farmers would benefit from having access to crops and cultivars that are more drought-resilient so they have greater options to practice deficit irrigation. This perspective is supported by Stokes and Howden (2010) who suggest that public sector support and investment are necessary for agricultural biotechnology and conventional plant breeding. Such investments might be best directed to crops that are major water users such as cotton and rice that, combined, conmed almost half of the water used by irrigated agriculture in 2000–2001 (Australian Bureau of Statistics, 2008).

Our results also show that the recent past drought in the Basin was much more extreme in terms of reduced water availability than the median 2030 climate change scenario projected by CSIRO. During the recent drought farmers were able to cope with the

Table 7
Irrigated land use change (%) in the Murray–Darling Basin under various climate change scenarios compared to the long-term historical average – *with inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Barwon–Darling	0	0	−99
Border rivers	0	0	−7
Campaspe	−17	−54	−98
Condamine–Balonne	0	0	−96
Eastern Mt Lofty ranges	0	0	−41
Goulburn–Broken	−2	−2	−92
Gwydir	−2	−2	−99
Lachlan	−23	−23	−86
Loddon–Avoca	−18	−51	−93
Macquarie–Castlereagh	−13	−13	−47
Moonie	−2	−2	−47
Murray	−2	−10	−81
Murrumbidgee	0	0	−78
Namoi	−17	−17	−97
Ovens	−1	−1	−49
Paroo	0	0	0
Warrego	0	0	−33
Wimmera	−2	−21	−22
Total	−5	−10	−81

Table 8
Profit change (%) in the Murray–Darling Basin under various climate change scenarios compared to the long-term historical average – *with and without inter-regional water trade.*

Region	Median 2030 scenario	Recent drought scenario	Modified dry extreme 2030 scenario
Without inter-regional water trade	−1	−7	−51
With inter-regional water trade	−1	−5	−44

water supply challenge. Although water use in the MDB fell by 52% from 2005/06 to 2008/09, the gross value of irrigated agricultural production only declined by 21% (Australian Bureau of Statistics, 2010). This suggests that the best practices developed by irrigators in managing in droughts are worth researching, documenting and, possibly, extending.

Beyond water trading, other adaptation strategies that can be used by farmers include: crop development; improvements in weather and climate information systems; and farm production innovations (Wreford et al., 2010). Hanjra and Qureshi (2010) also emphasise the need to develop drought-resilient crop varieties and, in a global context, the need to reform and liberalise international food trade.

6. Conclusions

In this study, we investigate region by region, the potential socio-economic impacts of the climate change predictions made by Commonwealth Scientific and Industrial Research Organisation (CSIRO). We employ a hydro-economic model to calculate the economic cost of reduced surface water availability. The model results provide a quantitative assessment of the water use, land use and net profits on irrigated agriculture in the Murray–Darling Basin due to climate change under several scenarios. The climate change impacts are calculated by region and by crop, and are calculated based on the reduced surface water availability due to climate change.

The results show that profit reductions in irrigated agriculture are much less than the reductions in surface water extractions. In part, this is because of water trading both within and across catchments that effectively transfers water use from low-value crops to relatively high-value ones. Under the median 2030 scenario, with or without inter-catchment water trade, the simulated profit loss is only 1%. This profit loss is similar to the income loss (1%) that is reported by Goesch et al. (2009) in the same climate change scenario. With inter-catchment water trade, we find that, over the entire Murray–Darling Basin, net profits declined by 5% under the recent drought scenario and by 44% in the modified dry extreme 2030 scenario (Table 8). By contrast, without inter-regional water trade, net profits declined by 7% under the recent drought scenario and by 51% in the modified dry extreme 2030 scenario (Table 8).

Overall, we find that the consideration of a dry, extreme climate future should be part of the adaptation framework in the Murray–Darling Basin, and possibly elsewhere. By contrast to the median projections, the impacts of dry, extreme climate are much greater. In the median climate change case the variability is well within the typical range experienced by farmers over the past century. In the extreme climate change case, investments in the development of drought tolerant crops and cultivars and the extension of best practice approaches to past droughts will likely be necessary.

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