Seidl, C., Wheeler, S. A., & Zuo, A. (2021). The drivers associated with Murray-Darling Basin irrigators' future farm adaptation strategies. In Journal of Rural Studies (Vol. 83, pp. 187–200). Elsevier BV

which has been published in final form at https://doi.org/10.1016/j.jrurstud.2020.10.048

Pre-accepted manuscript, published as:

Seidl, C, Wheeler, SA, Zuo, A. 2021. The drivers associated with Murray-Darling Basin irrigators' future farm adaptation strategies. Journal of Rural Studies 83, 187-200, https://doi.org/10.1016/j.jrurstud.2020.10.048

The drivers of Murray-Darling Basin irrigators' future farm adaptation strategies

Abstract:

Irrigators in the Murray-Darling Basin will need to adapt to future uncertainty, because of changes in markets, industry structures and climate. Such adaptation can be classified as expansive, accommodating or contractive strategies. Expansive adaptation strategies expand irrigation, accommodating strategies modify existing processes or crops without changing the size of the irrigation component of the farm, whereas contractive strategies reduce irrigation. Using data from a 2015-16 survey of 1,000 southern Murray-Darling Basin irrigators, 19 distinct planned future adaptation strategies are aggregated into expansive, accommodating and contractive adaptation indexes to analyse drivers of irrigators' future adaptation. While 90% of all irrigators are planning for at least one form of farm adaptation, there is some evidence that they prefer expansive adaptation strategies over accommodating and contractive adaptation strategies. In particular, succession planning and past adaptation experience have a statistically significant positive influence on all planned adaptation indexes. The influence of financial, human, natural, physical and social capital varies between adaptation types, with financial capital variables the strongest statistically significant driver for accommodating adaptation. Expansive and contractive adaptation are more strongly impacted by human and social capital variables.

Keywords: Adoption; climate change; planned behaviour; water markets; irrigation

1 Introduction

Climate change, changing economic circumstances and markets are major sources of uncertainty for farmers across the globe, requiring continuous adaptation well into the future (WEF, 2019). Traditionally, farmers have utilised economies of scale and irrigation technology to make farms more productive and to deal with a variable climate (de Roest et al., 2018). Although the drive to increase farm productivity through economies of scale will need to likely continue, this process will be constrained by land degradation and projected pressures on water resources stemming from climate change (IPCC, 2019). In particular, irrigators face increased uncertainty compared to dryland farmers, which is especially the case in Australia's key irrigated area, the Murray-Darling Basin (MDB) (Wheeler et al., 2018). Irrigators increasingly need to adapt to increased climate, market and water uncertainty. Some will seek to increase the irrigation component of the farm to capture more economies of scale and increased value of production, while others will seek to reduce their irrigated area in the future as a response to climate change.

Understanding what influences irrigators' future adaption plans is important, especially for policy-makers who design policies to influence both farm profitability and incentives to exit an industry (Zuo et al., 2015b). Adaptation has been defined as changes in decision-making and resource allocation in anticipating or responding to the prospect or reality of large-scale and long-lasting changes (Zilberman et al., 2012). Although there has been considerable research on farmer adoption behaviour (e.g. (Park et al., 2012; Morris et al., 2017; Bagheri et al., 2019; Chavas and Nauges, 2020)); empirical quantitative analysis of farmers' planned adaptation decisions, addressing complex, forward-looking and site-specific characteristics of adaptation processes (Below et al., 2012; Wheeler et al., 2013) has been less common.

Given that the future climate in the southern Murray-Darling Basin (sMDB) is predicted to be drier, with a higher frequency of extreme events (CSIRO, 2012), the ongoing need for water recovery for environmental purposes in the Basin (Grafton and Wheeler, 2018), and that market prices are driving significant agricultural change in the sMDB such that horticultural demand may exceed water availability in drought years (Loch et al., 2019), the sMDB provides an excellent case study to investigate the drivers of planned expansive, accommodating and contractive adaptation strategies.

This study uses a survey of 1,000 sMDB irrigators from 2015-16 to investigate the planned future adaptation strategies of sMDB irrigators. In particular, it seeks to understand: 1) the planned mix of expansive, accommodating or contractive farm adaptation; 2) the drivers of various planned expansive, accommodating, and contractive adaptation, and 3) the drivers across different strategies.

Insights from this study may be of significant assistance to policy-makers in Australia and abroad, when designing policies aimed at increasing irrigators' planned adaptation behaviour in an environment of profound climatic and economic uncertainty.

2 Adaptation literature review and background

Changing climatic and business environments lead to increased uncertainty for irrigators arising from imperfect information about future events, including missing information about the impacts of future uncertainty (Hardaker, 2015). Faced with multiple dimensions of uncertainty about the future, irrigators plan to implement measures and actions which they believe will provide net benefits for either one or more dimensions (Chavas and Nauges, 2020). Corresponding to the many dimensions of uncertainty, irrigators have an extensive set of adaptation strategies available to them (Smit and Skinner, 2002), Table A1 provides an overview. Specifically, strategies can be categorised relating to the timing of adaptation in relation to the change event (Fankhauser et al., 1999) or the type of adapting actor (Adger et al., 2005).

A large body of MDB adaptation literature focuses on the topics of water scarcity and drought (Quiggin et al., 2010; Dinh et al., 2017). These studies typically investigate the impacts/ implications of two major strategies: water trading, and irrigation infrastructure efficiency upgrades (e.g. (Alston et al., 2018; Wheeler and Marning, 2019). Water trading has been found an effective and flexible drought and climate change adaptation strategy in many studies (e.g. (Kirby et al., 2014; Qureshi and Whitten, 2014; Kirby et al., 2015). Farm exit, particularly in relation to water trading, has also recently received some attention, with climatic factors and commodity prices identified as major drivers (Wheeler and Zuo, 2017; Wheeler et al., 2020b). Irrigation infrastructure efficiency upgrades have been found beneficial for many individual irrigators (e.g. (Lee et al., 2012; Ticehurst and Curtis, 2015, 2018), but are seen to present maladaptation[1] at the Basin-scale (see Wheeler et al. (2020a) for an in-depth discussion).

Wheeler et al. (2013) first studied irrigation adaptation behaviour in the MDB and found that irrigators who believed their region was affected by climate change were less likely to be adapting their farm overall, were not planning to expand their farm, but were planning to change their crop mix and adopt more efficient irrigation infrastructure, and were more likely to be planning to decrease their irrigated area. Older irrigators with greater reliance on off-farm income were more likely to not plan to purchase land or change their crop mix. Dinh et al. (2017) used data from 568 MDB irrigators and 979 dryland farmers to categorize drought adaptation strategies as water-, investment-, land-, output-, input-related and financial help.

---

[1] Maladaptation in this context refers to the negative consequences of implemented adaptation measures (Neset et al., 2019).

They found that irrigators employed more adaptation strategies than dryland farmers, with investment-related and water-related the most common strategy type employed. Irrigators more dependent on farm income, and running larger, annual, and more intensive farming operations were more likely to adapt. However, 30% of surveyed irrigators did not employ any strategy.

Various forms of Australian drought policy have tried to influence farmer adaptation. Policy initially treated drought as a natural disaster with associated relief payments, but later perceived it as a business risk for and to be managed by farmers, albeit there is allowance for "exceptional" circumstances and an increased emphasis on exit packages (Botterill and Chapman, 2004; Zuo et al., 2015b).

The majority of adaptation studies have analysed the drivers for already implemented adaptation behaviour; observing what strategies were implemented and why (e.g. (Moniruzzaman, 2015; Wang et al., 2015; Abid et al., 2016)). One particular issue with this is controlling for endogeneity (namely the causal impact) between past behaviour using current socio-economic characteristics.

In contrast, this study focuses on adaptation behaviour irrigators' *plan* to implement in the mid-near future (namely the next five years). To model future adaptation behaviour, a number of studies (e.g. (Feola et al., 2015; Li et al., 2017) have employed Ajzen's (1991) *Theory of Planned Behaviour* or related frameworks, such as the *Theory of Reasoned Action* (Ajzen, 2012). Despite the caveat that intention to implement a behaviour is not the same as enactment, Wheeler et al. (2013) and Wheeler and Zuo (2017) found it was a strong indication in the MDB context. For example, Wheeler et al. (2013) who found that Goulburn irrigators' intentions for farm management and water trading reasonably closely matched their actual behaviour, with intentions slightly higher than actual enactment. Modelling irrigators' adaptation intentions is therefore considered an appropriate theoretical approach for this study.

Five Capitals Influencing Irrigators' Adaptive Capacity

This study is interested in understanding the different drivers of irrigators' planned adaptation, across a range of potential strategies. Planned adaptation is analysed in three indexes: 1) expansive adaptation that increases or enhances the irrigation component of a farm enterprise; 2) accommodating adaptation that changes the farm structure without impacting the irrigation component; and 3) contractive adaptation that reduces the irrigation component.

To this end, we utilise a modified version of Ajzen's *Theory of Planned Behaviour*. We express the intent-mitigating (unobservable) concept of "perceived behavioural control" (Ajzen, 1991), as irrigators' adaptive capacity (observable) in the form of the five types of capital by Ellis (2000). **Error! Reference source not found.Error! Reference source not found.** illustrates the study's theoretical framework.

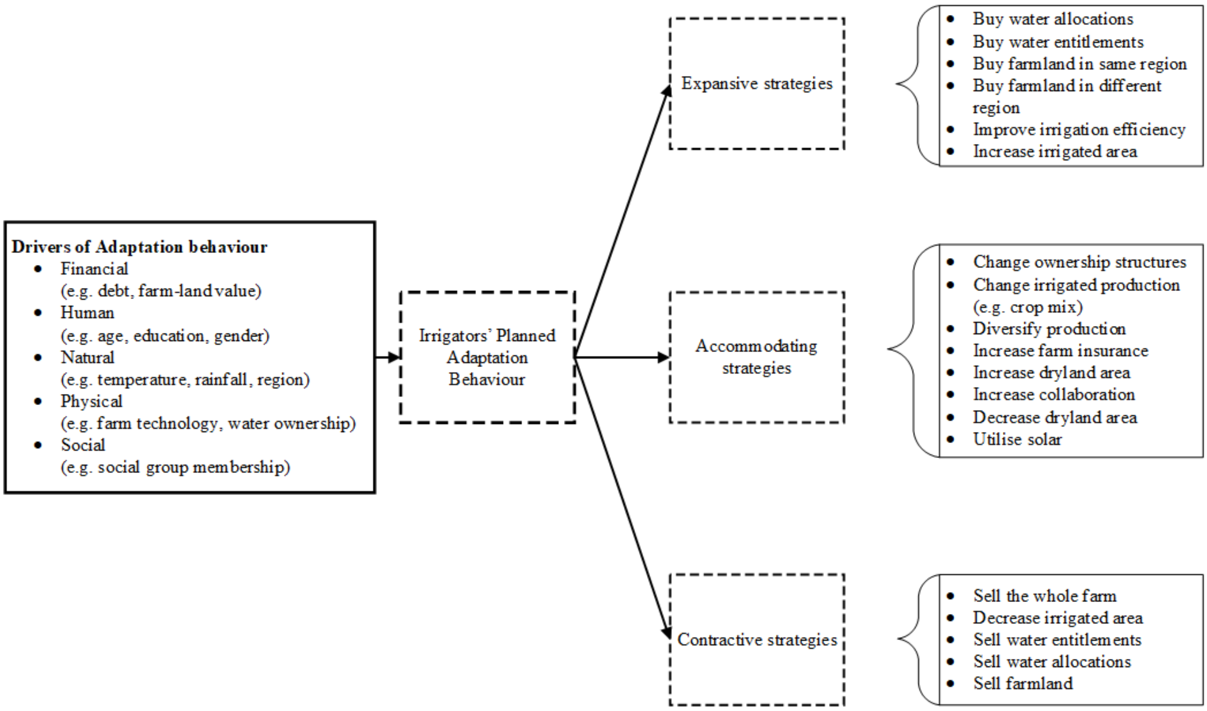

Figure 1 Modelling the Influence of the Five Types of Capital on Irrigators' Planned Behaviour and examples from the study data

Source: Adapted from Wheeler et al. (2013)

Note: Individual expansive, accommodating and contractive strategies reflect the strategy questions, and their format, asked in the irrigator survey and therefore do not represent a comprehensive total list.

An irrigator's ability to adapt to a changing environment is determined by their adaptive capacity (Ellis, 2000; Adger et al., 2005). This adaptive capacity is dependent upon numerous influences, but certainly includes socio-economic factors, as well as climatic and environmental characteristics. To simplify these influences, Ellis (2000) suggests grouping them in relation to five different types of capital: financial, human, natural, physical, and social capital. We define financial capital as the economic and financial characteristics of an irrigation farm (e.g. debt, farm income); human capital as unique characteristics of the irrigator (e.g. education, age); natural capital as the physical setting of the farm (e.g. temperature, rainfall); physical capital as the characteristics and technology of irrigated production (e.g. farm size, irrigation technology); and social capital as the characteristics of the irrigator’s social unit and their interactions (e.g. membership in social groups, farm extension, social cohesion).

The concept of the five types of capital is now commonly used in the adaptation literature (e.g. (Ng’ang’a et al., 2016; Li et al., 2017). However, economic and sociological factors may be of differing importance for various types of agricultural adaptation strategies (Morrison et al., 2011).

Table A2 in Appendix A provides an overview of key literature findings in regards to drivers of farm adaptation behaviour, from the perspective of the five types of capital.

3 Data and Methodology

3.1 Study Area

The sMDB spans three states New South Wales (NSW), South Australia (SA), Victoria (VIC) and the Australian Capital Territory (ACT) in south-eastern Australia (Figure 2).

Figure 2 Map of the Murray-Darling Basin

Source: MDBA (2016)

The MDB produces food and fibre worth around AU$22 billion annually, was home to around 8,850 irrigators in 2018-19 (ABS, 2020). Irrigation is supported by water entitlements (a right to extract a share of an available water source) of different security/reliability and corresponding water allocations. There are three main securities (high, general and low).[2] An allocation is the actual volume of water extracted on an entitlement in a given year.

---

[2] A high security entitlement yields the full extraction amount in 90-95 out of 100 years (Zuo et al., 2016).

Entitlements and allocation can be traded (see Seidl et al. (2020), and Grafton and Wheeler (2018) for water trading and water reform history).

Survey data is from an irrigator telephone survey, conducted from October-November 2015 in the sMDB. The data consists of 1,000 responses (overall response rate 51% or 73% including those who agreed to be surveyed but were not given sample sizes were reached) from randomly sampled irrigators (not dryland farmers) across three states (NSW, Victoria and SA).[3] The survey collected information on irrigators' attitudes, socio-economic and farm characteristics, past farm management and adaptation strategies and future/planned management and adaptation strategies in the next five years.[4] For more discussion on the survey data collection see Daghagh Yazd et al. (2019) and Wheeler et al. (2018). Gridded historic temperature, rainfall and evaporation data from the Bureau of Meteorology was geo-matched to the post-codes of each survey respondent and incorporated into the survey data set.

This study includes a comprehensive list of 19 strategies planned to be undertaken by irrigators from 2015-16 onwards (see Table 1), which is one of the most comprehensive existing analyses of planned behaviour (for example, Wheeler et al. (2013) modelled only eight strategies using 2010-11 data and did not consider modelling as grouped themed strategies).

---

[3] Given irrigator populations in the MDB from the three states (1156 in SA, 3985 in VIC, and 3345 in NSW in 2015-16 (ABS, 2017a)), the final sample sizes of NSW (419), VIC (372) and SA (209) will result in relative standard errors (RSE) of 4.7%, 5.1% and 6.6% respectively (e.g. indicating low RSEs), for an estimated proportion of 0.5. As an indication, the ABS suggests that RSEs>25% are subject to high sampling error and should be used with caution.

[4] Land lease data was not collected as leased land in 2015-16 was only 2% of total agricultural land in Victoria, and only 0.8% and 1.8% in NSW and SA respectively (ABS, 2017b).

3.2 Methodology

3.2.1 Dependent variables

This study has three main dependent variables, namely indexes for: 1) expansive adaptation; 2) accommodating adaptation; and 3) contractive adaptation. Table 1 provides an overview of each dependent variable and the summary statistics for the individual planned adaptations and the planned adaptation indexes models.

Table 1 Planned adaptation index variable definitions and summary statistics (n=1,000)

Dependent variable	**Index mean** (std. dev.)	**Min**	**Max**	**Construction variables: Planned adaptation strategies (yes=1, 0=otherwise)** ***In the next 5 years, are you planning to:***	**% of 'yes' responses**
Planned expansive irrigation adaptation index	2.2(1.7)	0	6	Purchase water allocations	56
				Purchase water entitlements	30
				Purchase any farm land near current properties	29
				Purchase any farm-land in different zones/regions for risk purposes	11
				Improve the efficiency of your irrigation infrastructure	67
				Increase irrigated area	29
Planned accommodating farm adaptation index	2.3(1.8)	0	7	Change ownership structures	29
				Change crop mix	48
				Diversify production	40
				Increase farm insurance	39
				Decrease dryland production area	9
				Increase any collective bargaining or collaboration with other farmers	22
				Increase dryland production area	20
				Utilise solar-power energy and battery system for your irrigation pumping	31
Planned contractive irrigation adaptation index	1.3(1.4)	0	5	Think about selling the whole farm	53
				Decrease irrigated area	15
				Sell water allocations	38
				Sell water entitlements	15
				Sell any farm-land	22

The planned expansive, accommodating and contractive adaptation indexes are constructed by summing up irrigators' positive responses to 19 questions about planned implementation of expansive, accommodating and contractive adaptation strategies (see Table 1).

Note, no assumptions about the relative importance of different strategies are possible to make, and since our data contain no information about the degree of implementation of these planned strategies, the index components are unweighted, following the approach in Hoffmann et al. (2009) and Wheeler et al. (2013), implicitly assuming that choosing more strategies (a higher index count) represents a higher degree of adaptation. Index construction also assumes that planned adaptation strategies are chosen independently. However, we find a correlation coefficient of 0.53 between the planned expansive and accommodating indexes, and -0.28 between the planned expansive and contractive indexes. The correlation coefficient between the accommodating and contractive index is -0.02.[5] Therefore, we used a Seemingly Unrelated Regression (SUR) model (see model section) to minimise any potential bias in our estimations. These correlations may stem from the existence of compound adaptation strategies (e.g. sell dryland to increase irrigated area), making the choice of planned adaptation strategy not independent (Kassie et al., 2015; Vigani and Kathage, 2019). We tested for this by also modelling potential compound strategies using multivariate probit models, results of which are not reported in this paper (but available upon request). Examining the statistical dependence of the planned adaptation strategies involved, we found some limited evidence of compound strategies existing (i.e. strategies not being statistically independent, e.g. *selling entitlement and more dryland* or *less irrigated area and more dryland),* possibly causing the moderate and weak correlation of the dependent variables.

3.2.2 Independent variables

The literature (e.g. Table A2, Appendix A) was used to identify important explanatory variables, which were then sourced from the survey data and secondary data sets (e.g. gridded

---

[5] Note that tetrachoric correlation coefficients between individual adaptation strategies were consistently lower than 0.7.

historic temperature, rainfall and evaporation data comes from the Bureau of Meteorology). A list of independent variables used in the model, including descriptive statistics and groupings into the five types of capitals, is provided in Table A3, Appendix A.[6]

3.2.3 Model

As outlined, we grouped the 19 binary irrigators' planned adaptation questions into three indexes: the planned expansive, accommodating and contractive adaptation indexes, serving as the dependent variables for three models. A variety of different methodologies were tested, including negative binomial, Poisson and multivariate linear regression. The most robust results were provided by Seemingly Unrelated Regressions (SUR) (Zellner, 1963).[7] The SUR method applies generalised ordinary least-squares (OLS) simultaneously to a system of equations; coefficient estimators so obtained are asymptotically more efficient than those obtained by an equation-by-equation approach. For example, we modelled:

$$(1) \quad y = X\beta + u$$

where y is the dependent variable (either of the three adaptation indexes); X is the matrix of all independent variables (note every index uses the same set of independent variables); β is the vector of regression coefficients and u the vector of random error terms.

Attention has to be given to the influence of climate change beliefs (independent variable) on adaptation decisions (dependant variable). While irrigators likely adapt more if they believe in being at risk from climate change, irrigators conversely may believe more strongly in being at risk from climate change *because* they plan to adapt for it. Some adaptation studies

---

[6] We also used the squared functional form of age, debt, farm income and land value, enabling the identification of threshold effects (namely to investigate whether if past a certain point, the relationship changes).

[7] Model robustness was determined on lowest Akaike's and Schwarz's Bayesian information criteria values, tests for goodness-of-fit and overdispersion, and stability of independent variable significance.

(e.g. (Hogan et al., 2011; Park et al., 2012)) argue that the causal relationship runs from climate change belief to adaptation, but the true relationship might be endogenous, with each influencing the other. We use a control function approach, suggested in Nauges and Wheeler (2017) and detailed in Wooldridge (2010, 2015), to address endogeneity and to obtain consistent and asymptotically normal estimates:

$$(2) \quad CC\_risk = V\theta + \kappa CC\_plan + E\_instr$$

Namely: an irrigator's climate change risk perception (CC_risk) is the dependent variable regressed on the vector of independent variables (V)[8] and their climate change planning on farm (CC_plan), our instrument variable. A good instrument needs to be correlated with climate change risk perceptions, but uncorrelated with the error term u in our main equation. Climate change planning on farm was found to be an appropriate instrument for climate change risk perception.[9]

We first estimate (2) using OLS and obtain the estimated residuals $E\_\widehat{\imath nstr}$. We then estimate (3) using SUR, an augmented version of (1) which includes the estimated residuals as an additional independent variable:

$$(3) \quad y = X\beta + \lambda E\_\widehat{\imath nstr} + \omega$$

Note that the SUR model estimates equation (3) for every index simultaneously. Assuming climate change planning on farm is a valid instrument, the SUR estimation provides unbiased estimates of β and λ. $\lambda E\_\widehat{\imath nstr}$ is the "control function" used to test for endogeneity. A rejection of the null assumption that $\lambda = 0$ would be evidence for endogeneity of the climate change risk perception variable, and a positive (negative) λ coefficient would indicate that the

---

[8] Note that V contains the same variables as X, but without CC_risk: (X = V + CC_risk).

[9] This instrument was also used in Wheeler et al. (2013).

impact of irrigators’ climate risk perception on the planned adaptation strategy indexes is under-estimated (over-estimated) if endogeneity is not controlled for.

Modelling with and without outliers, and correlation and VIF analysis were used to identify and exclude influential outliers and any seriously collinear variables (using correlation coefficients of 0.7 and above and VIFs above 10).

4 Results

4.1 Descriptive statistics of expansive, accommodating and contractive indexes

Ninety percent (90%) of irrigators planned to employ more than one type of index strategy and only 1% planned to employ no strategies. Comparing the proportion of individual adaptation strategies chosen per index (Table 2),[10] irrigators in the southern MDB seem to choose on average a higher proportion of expansive adaptation strategies (37%), as compared to accommodating (29%) or contractive adaptation (29%) strategies (reflecting findings in Wheeler et al. (2013).

Table 2 Descriptive statistics of expansive, accommodating and contractive indexes (n=1,000)

Index	**Mean proportion of all index strategies chosen**	**Irrigators using more than one individual adaptation strategy (out of 19 adaptations)**	**Irrigators using only one type of index strategy (out of 3 index types)**	**Most nominated individual adaptation strategy**
Expansive index	37%***	81%	3%	Improve irrigation infrastructure efficiency
Accommodating index	29%	83%	1%	Change irrigated production
Contractive index	29%	74%	7%	Selling the whole farm

---

[10] Since the indices do not comprise the same number of questions, we compared: $\frac{number\ of\ planned\ strategies\ chosen\ (index\ count)}{number\ of\ possible\ planned\ strategies\ (maximal\ possible\ index\ count)}$. Unpaired t-tests revealed that the mean percentage of chosen planned accommodating and contractive strategies are not significantly different, but the mean percentage of planned expansive strategies is statistically significantly larger compared to both of the others ($p<0.01$).

Note: *** Using unpaired t-tests show irrigators choose a higher proportion of planned expansive adaptation strategies than planned accommodating and contractive strategies ($p<0.01$)

Despite the preference for expansive adaptation strategies overall, the strength of this result should not be overestimated due to the construction of the planned expansive adaptation index. A high incidence of planned water allocation purchase (56% of irrigators, see Table 1) is not surprising, given that water allocation trading is common for sMDB irrigators (Seidl et al., 2020).

In addition, although many irrigators would like to purchase extra water entitlements, to increase water supply security expansion operations, or as an investment (Haensch et al., 2019), water market prices are highly variable, and increase significantly in times of water scarcity, decreasing the ability of irrigators to buy new water entitlements. Hence, such changes can mean that actual behaviour does not match planned behaviour.

4.2 SUR Results

The SUR analysis shows different capital drivers have varying influence on irrigators' planned expansive, accommodating and contractive adaptation (Table 3).[11]

Comparing Table A2 and Table 3 reveals a number of factors broadly follow the directions predicted by past literature. The following section discusses the drivers by the various capitals.

---

[11] Sensitivity analysis was done for the influence of states and industry. This did not contribute to the explanatory power of the model in a meaningful manner and is therefore not reported here.

Table 3 SUR regression of planned expansive, accommodating and contractive adaptation

	Planned adaptation indexes		
	Expansive	**Accommodating**	**Contractive**
VARIABLES	**Coefficient**[1] (standard error)		
Financial capital			
Farm debt	1.24***(0.37)	1.09***(0.42)	-0.24(0.36)
Farm debt squared	-0.81***(0.29)	-0.74**(0.33)	0.40(0.29)
Farmland value	-0.25(0.21)	-0.82***(0.23)	-0.05(0.20)
Farmland value squared	0.08(0.06)	0.22***(0.07)	0.01(0.06)
Net farm income	2.03(1.99)	4.01*(2.22)	2.32(1.94)
Net farm income squared	-6.36(7.49)	-16.82**(8.32)	-11.92(7.30)
Number of insurances	0.07**(0.03)	0.09**(0.04)	-0.04(0.03)
Off-farm income	0.00**(0.00)	0.00(0.00)	0.00(0.00)
Productivity change	0.09**(0.03)	-0.01(0.04)	-0.14***(0.03)
Human capital			
Age	-0.01(0.03)	0.01(0.03)	0.01(0.03)
Climate change risk perception	0.54***(0.15)	0.67***(0.17)	0.10(0.15)
Low education	0.03(0.11)	0.10(0.12)	0.25**(0.11)
Male gender	0.40***(0.12)	0.17(0.13)	0.01(0.12)
Succession plan	0.54***(0.09)	0.46***(0.10)	-0.63***(0.08)
Has whole of farm plan	0.11(0.10)	0.31***(0.11)	-0.01(0.09)
Natural capital			
Average historic water allocation	0.04(0.19)	0.09(0.21)	-0.15(0.18)
Historic net rainfall	0.00(0.00)	0.00(0.00)	0.00(0.00)
Historic temperature variability	-1.68(1.44)	1.36(1.59)	-0.51(1.40)
South Australia	-0.24(0.27)	0.26(0.30)	-0.54**(0.27)
Victoria	-0.15(0.11)	-0.11(0.13)	-0.19*(0.11)
Physical capital			
Carry-over use between 2014-2016	0.12(0.10)	0.19*(0.12)	-0.10(0.10)
Excess water	-0.23**(0.10)	-0.06(0.11)	0.61***(0.10)
Farm Size	0.00(0.00)	0.00(0.00)	0.00(0.00)
Industry: Broadacre	0.15(0.16)	-0.22(0.18)	-0.31**(0.16)
Industry: Dairy	0.06(0.18)	-0.20(0.20)	-0.28(0.17)
Industry: Livestock	0.09(0.17)	-0.30(0.19)	-0.48***(0.16)
Majority of farm area under drainage	0.01(0.10)	-0.01(0.11)	0.07(0.09)
Majority of farm area under drip irrigation	-0.26*(0.15)	-0.34**(0.16)	-0.07(0.14)
Number of employees	0.01(0.01)	0.01(0.01)	-0.02(0.01)
Water application rate	0.00(0.01)	-0.01(0.01)	0.00(0.01)
Water ownership	-0.06**(0.03)	-0.01(0.03)	0.03(0.03)
Past behaviour			
Past index	0.50***(0.03)	0.61***(0.03)	0.22***(0.04)
Control function residual	-0.57***(0.18)	-0.64***(0.20)	-0.08(0.17)
Constant	1.85(1.43)	-0.64(1.59)	2.08(1.40)
AIC	8560.36	8560.36	8560.36
BIC	9064.96	9064.96	9064.96
Observations	903	903	903
R-squared	0.54	0.49	0.24

Notes: *** p<0.01, ** p<0.05, * p<0.1

[1] coefficients and standard errors (in brackets) rounded to two decimal points

4.2.1 Financial capital

Financial capital had the most statistically significant variables influencing the dependent variables of adaptation (especially expansive and accommodating adaptation). In particular, farm debt levels are highly significant and positive drivers for planned expansive and contractive adaptation, albeit at a decreasing rate, signified by the significant negative influence of farm debt squared. In contrast to other studies, which often treat access to credit as a qualitative/binary variable (e.g. (Bryan et al., 2013; Touch et al., 2016)), our results allow us to quantify the benefits of credit access versus the hampering effect of larger farm debt. At a threshold level of around AUD$765,000 for expansive and AUD$736,000 for accommodating adaptation, the negative influence of very large farm debt squared outweighs the positive influence of farm debt.

Increases in net farm income were weakly statistically significant in positively influencing planned accommodating adaptation, and increased farm productivity was a statistically significantly positive (negative) influence on planned expansive (contractive) adaptation. This is in line with expectations: higher income increases adaptation affordability, while irrigators who have been improving productivity over the last five years are less likely to plan to employ contractive measures, such as farm exit or decreased irrigation area.

The strongly significant negative impact of farmland value on planned accommodating adaptation is surprising: contributing to irrigators' wealth, one would expect a positive relationship mirroring the commonly observed influence of farmer wealth (Roco et al., 2014; Li et al., 2017). Upon reviewing the individual behaviour models (see Seidl (2020)), the result is driven by a significant negative impact of farmland value on planned insurance uptake. One possible explanation is that wealthier irrigators, expressed by higher farmland values, may prefer to self-insure (i.e. wearing potential losses out of their capital base, and off-setting risk though diversified income or other measures) rather than take out insurance.[12] This relationship between farm-land values and insurance uptake has also been found in other studies (e.g. (Sherrick et al., 2004; Mishra and Goodwin, 2006).

The current level of insurance, expressed by the number of different insurance contracts, is a significantly positive impact on planned expansive and accommodating adaptation. We interpret current insurance level as a proxy for irrigators' risk aversion, with more insurance corresponding to higher risk aversion.[13] Thus, our results support findings in other studies that increasing risk aversion increases adaptation (Wheeler et al., 2013; Zuo et al., 2015a; Tambo, 2016).

4.2.2 Human and social capital

Human and social capital factors play an important role in planned adaptation. Past adaptation experience, expressed by the past adaptation index value, climate change risk perception and succession planning are highly statistically significant positive drivers for planned expansive and accommodating indexes. While past experience was also a significant positive driver for the planned contractive adaptation index, succession planning shows a significant negative influence. Male gender was a significantly positive driver for the expansive index, and low education a significant positive driver for the contractive index.

The influence of past experience was expected and in line with the literature (e.g. (Nicholas and Durham, 2012; Wheeler et al., 2012): past experience shows familiarity with, and

---

[12] As profit-oriented entities, insurance providers' premiums include a risk premium above the stochastic fair value of incurred insurance pay-outs. Wealthy irrigators, due to their higher capacity and resources to manage risks, may choose to employ their own risk management strategies leading to payouts equivalent to the stochastic fair value of incurred damages, thus saving themselves the premium payments to commercial insurance providers.

[13] Using self-reported risk aversion instead of current level of insurance was not significant and did not improve model quality.

learning about, the technologies/strategies involved (Chavas and Nauges, 2020). Another aspect is that past adaptation can lead to path dependence based on the technology/strategy used (e.g. irrigation infrastructure improvements) and therefore increase the likelihood of continuing to use the same measure (Neset et al., 2019). On the flipside, negative past experiences may provide disincentives to undertake, or continue to undertake, a certain adaptation strategy in the future (Simtowe and Mausch, 2019). In our data, the effect of a negative past experience is statistically superseded by the positive effect of experience and learning associated with past adoption of a strategy, leading to an overall positive influence for planned adaptation.

The positive influence of having a nominated successor was also expected: irrigators planning their succession would prefer to hand over a larger and or improved, rather than a smaller, farm (Li et al., 2017).

Irrigators' climate change risk perceptions are significant positive drivers for planned expansive and accommodating adaptation, confirming growing evidence in the literature (Alam, 2015; Jianjun et al., 2015).[14] We found a significant negative endogenous relationship between climate change risk perceptions and expansive and accommodating indexes. The negative coefficient of the control function suggests the impact of risk perceptions for expansive and accommodating adaptation are likely over-estimated, while the presence of endogeneity hints at a two-way causality: irrigators adapt more because they believe to be affected by climate change, and undertaking planned behaviour can influence back on behavioural change. Further work in this space is warranted.

---

[14] Note that in contrast to earlier climate change adaptation studies (e.g. (Arbuckle et al., 2013)), we use the concept of *perceived affectedness* by climate change as factor for adaptation behaviour (van der Linden, 2017).

4.2.3 Natural and physical capital

Natural and physical capital variables, such as geography, location, farm technology, farm size and climate are common drivers of adaptation behaviour. In our case, excess water holdings and increase area of the farm under drip irrigation are (weakly) statistically significant negative influences on the expansive adaptation index. Excess water holdings are a significant positive driver for the planned contractive adaptation index, while being in Victoria or South Australia, broadacre and livestock industry are negative drivers.

This supports recent findings by Wheeler et al. (2020b) that farm exit (and or shrinking of irrigation in our case) in the sMDB is driven by climatic factors and industry characteristics. Our results regarding excess water holding support findings by Wheeler and Cheesman (2013), showing irrigators sell excess water entitlements (contractive strategy) for environmental water recovery but keep irrigating. That irrigators sell more water allocations (contractive strategy) if they own excess water makes intuitive sense and is well documented (e.g. see Loch et al. (2012).

5 Discussion

Faced with multiple dimensions of future uncertainty, sMDB irrigators plan to use a mix of expansive, accommodating and contractive adaptation, with all indications that planned expansive adaptation is preferred.

Financial, human, natural, physical and social capital all influence planned adaptation, but their influence varies within expansive, accommodating and contractive adaptation. Financial capital variables are the most important driver for planned accommodating adaptation, but also play an important role for planned expansive adaptation. Farm debt, risk aversion (expressed by number of insurances), and productivity change are the most influential financial capital variables, confirming the results of other studies (e.g. (Tambo, 2016; Touch et al., 2016; Li et al., 2017). Surprisingly, planned contractive adaptation is largely unaffected (with the exception of productivity change) by financial capital, despite the expected link between poor farm financials (high debt, low income) and land sale, water entitlement sale, and farm exit. Instead, industry and state dummies have a more pronounced impact, showing the importance of regional climate and industry characteristics (Wheeler et al., 2020b).

Human and social capital play an important role for all adaptation indexes, in particular past adaptation experience and succession planning. Human and social capital factors are the most important drivers for the expansive and contractive adaptation indexes. The significance of climate change risk perception for the expansive and accommodating indexes illustrates the importance of climate change affectedness (van der Linden, 2017). Although some variables, such as past adaptation experiences and succession planning, influence planned expansive, accommodating and contractive adaptation simultaneously, the majority of drivers vary between different adaptation types. Financial capital variables (farm debt, farmland value, income, and number of insurances) are the major drivers for planned accommodating adaptation, whereas human and social capital (climate change risk perception, succession and past experiences) are more important for planned expansive and contractive adaptation.

While some studies use a weighted adaptation index approach (Below et al., 2012), given the data limitations about the magnitude of adaptation strategies in this study, this was not possible. Another data limitation is that, apart from social group membership, social capital concepts such as social participation and social cohesion were not explored in our survey. Future research should aim to include a more comprehensive list of social capital variables and the intensity of planned adaptation into the analysis to provide a more nuanced picture of drivers for adaptation, and to allow for a ranking/weighting of different (and compound) planned adaptation strategies.

Confirming the findings by Dinh et al. (2017), we find most irrigators plan to upgrade their irrigation infrastructure and engage in water allocation purchases. In contrast, we find a significantly lower number of irrigators plan to not use any adaptation strategies, while age and farm size play no statistically significant role for planned adaptation.[15] This likely indicates that sMDB irrigators across all ages, farm sizes and types increasingly recognise the need for adaptation and plan accordingly.

Our results suggest readjusting drought and adaptation policy may be beneficial, particularly in view of future drought and climate change. Through subsequent drought policies (e.g. the National Drought policy), the Australian government has encouraged farmers to be self-reliant and develop their own risk management strategies, relying on financial incentives, such as, the Income Equalisation Deposits scheme (Botterill, 2010). However, the government has traditionally provided assistance for "exceptional" droughts, hence indirectly compromising irrigators' individual risk management efforts, and the establishment of competitive insurance products (e.g. yield insurance) (Nauges et al., 2016). This ad hoc drought support has fostered attitudes which do not adequately protect farmers from insolvency risks (Botterill et al., 2017), while encouraging farmers to build financial reserves may be a more effective risk management approach (Botterill, 2010).

The findings of this paper have implications for adaptation policies in other countries, especially where access to finance and knowledge play a limited role. Including non-financial incentives in policies fostering planned adaptation may be effective in reaching desired outcomes. In particular, supporting succession planning can have a meaningful impact on future adaptation efforts, especially in countries which experience aging farmer population and low farm succession rates (Lobley et al., 2010; Leonard et al., 2017; Cavicchioli et al.,

---

[15] This extends to the absence of past strategy use: only 2% of our irrigators did not use any strategy in the past 5 years.

2018). Financial incentives should give stronger emphasis to supporting irrigators' risk management efforts, given the propensity of wealthier farmers to self-insure, rather than managing risk through commercial insurance providers (Sherrick et al., 2004; Mishra and Goodwin, 2006). Supporting irrigators' risk management efforts is especially prudent in countries where the availability of farm insurance products is limited, such as Australia (Nauges et al., 2016). Providing non-monetary incentives and better support for irrigators' private risk management efforts, potentially through improved climate change forecasting, also translating into tangible risk implications, could increase planned adaptation and potentially foster the emergence of commercial insurance products (Nadolnyak et al., 2008; Crane et al., 2011; Carriquiry and Osgood, 2012). Policy-makers aiming to incentivise planned adaptation should clearly identify which type of adaptation they are targeting and which capital factors have the strongest corresponding influence. This will potentially allow for more targeted and cost-effective incentive policies.

6 Conclusion

With increasing pressures from climate change, agricultural industry restructuring and globalisation, irrigators will continuously need to adapt to an uncertain and risky future. This study explored southern MDB irrigators' preferences (n=1,000 in 2015-16) and drivers for different planned adaptation types, modelling three indexes: 1) planned expansive adaptation: increases farm irrigation; 2) planned accommodating adaptation: alters farm structure and production practices while leaving the irrigation unchanged; and 3) planned contractive adaptation: decreases irrigation.

The majority of irrigators are planning adaptation from multiple strategy choices, with evidence that planned expansive adaptation is preferred over accommodating and contractive adaptation. While financial, human, natural, physical and social capital variables all influence planned adaptation, their role varies between planned expansive, accommodating and contractive adaptation strategies.

Financial capital drivers seem to be the most influential for planned accommodating adaptation, in particular farm debt, farmland value and farm income. Farm debt, off-farm income and productivity change influence planned expansive adaptation, whereas planned contractive adaptation is only influenced by productivity change. Natural and physical capital factors play an important role for planned contractive adaptation, with location in a particular state and industry particularly important. On the other hand, human and social capital variables are common drivers across all types of planned adaptation. In particular, farm succession planning and past adaptation experiences strongly impact planned expansive, accommodating and contractive adaptation.

Our study illustrates the importance of non-financial factors for irrigators' planned adaptation, particularly of succession planning and adaptation experience. Knowing what influences planned expansive, accommodating and contractive adaptation allows policy-makers to design targeted and effective policies to incentivise increased adaptation of a particular type. Australian drought policy shows that drought relief measures can be counterproductive and hamper irrigators' risk management efforts. Aiding irrigators' risk management efforts by improving climate change forecasting or succession planning support, reforming drought policy such that it also draws on non-monetary incentives, and policies targeting different types of adaptation directly could increase future adaptation to climate change and water scarcity.

Funding sources

This work was supported by the Australian Research Council [DP200101191 and FT140100773], and a University of Adelaide International Postgraduate Scholarship.

Acknowledgements

We are grateful for the helpful comments of the journal's reviewers in improving this manuscript.

References

Abid, M., Schneider, U.A., Scheffran, J., 2016. Adaptation to climate change and its impacts on food productivity and crop income: Perspectives of farmers in rural Pakistan. J. Rural Stud. 47, pp. 254-266. DOI:http://dx.doi.org/10.1016/j.jrurstud.2016.08.005

ABS, 2017a. Water Use on Australian Farms 2015-16. Australian Bureau of Statistics, Canberra.

ABS, 2017b. Agricultural Land and Water Ownership, 2015-16. Australian Bureau of Statistics, Canberra.

ABS, 2020. Water Use on Australian Farms, 2018-19. Australian Bureau of Statistics, Canberra.

Adger, N.W., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Glob. Environ. Change 15, pp. 77-86.

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50, pp. 179-211. DOI:https://doi.org/10.1016/0749-5978(91)90020-T

Ajzen, I., 2012. Martin Fishbein’s Legacy: The Reasoned Action Approach. Ann. Am. Acad. Political Soc. Sci. 640, pp. 11-27. DOI:10.1177/0002716211423363

Alam, K., 2015. Farmers’ adaptation to water scarcity in drought-prone environments: A case study of Rajshahi District, Bangladesh. Agric. Water Manag. 148, pp. 196-206. DOI:http://dx.doi.org/10.1016/j.agwat.2014.10.011

Alston, M., Clarke, J., Whittenbury, K., 2018. Limits to adaptation: Reducing irrigation water in the Murray-Darling Basin dairy communities. J. Rural Stud. 58, pp. 93-102. DOI:https://doi.org/10.1016/j.jrurstud.2017.12.026

Arbuckle, J.G., Morton, L.W., Hobbs, J., 2013. Farmer beliefs and concerns about climate change and attitudes toward adaptation and mitigation: Evidence from Iowa. Clim. Change 118, pp. 551-563. DOI:10.1007/s10584-013-0700-0

Bagheri, A., Bondori, A., Damalas, C.A., 2019. Modeling cereal farmers’ intended and actual adoption of integrated crop management (ICM) practices. J. Rural Stud. 70, pp. 58-65. DOI:https://doi.org/10.1016/j.jrurstud.2019.05.009

Below, T.B., Mutabazi, K.D., Kirschke, D., Franke, C., Sieber, S., Siebert, R., Tscherning, K., 2012. Can farmers’ adaptation to climate change be explained by socio-economic household-level variables? Glob. Environ. Change 22, pp. 223-235. DOI:http://dx.doi.org/10.1016/j.gloenvcha.2011.11.012

Botterill, L.C. and Chapman, B., 2004. An income-related loans proposal for drought relief for farm businesses. Aust. J. Public Adm. 63, pp. 10-19. DOI:10.1111/j.1467-8500.2004.00386.x

Botterill, L.C., 2010. Risk management as policy. The experience of Australia's National Drought Policy. In: López-Francos, A. (Ed.), 2010. *Economics of Drought and Drought Preparedness in Climate Change Context*, Zaragoza.

Botterill, L.C., Chapman, B., Kelly, S., 2017. Revisiting revenue contingent loans for drought relief: government as risk manager. Australian J. Agr. Resource Econ. 61, pp. 367-384. DOI:10.1111/1467-8489.12213

Brooks, N. and Adger, N.W., 2005. Assessing and enhancing adaptive capacity. In: Lim, B., Burton, I., Malone, E., Huq, S. (Eds.), 2005. *Adaptation policy frameworks for climate change: Developing strategies, policies and measures*, Cambridge University Press, New York.

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., Herrero, M., 2013. Adapting agriculture to climate change in Kenya: Household strategies and determinants. J. Environ. Manage. 114, pp. 26-35. DOI:http://dx.doi.org/10.1016/j.jenvman.2012.10.036

Carriquiry, M.A. and Osgood, D.E., 2012. Index Insurance, Probabilistic Climate Forecasts, and Production. J. Risk Ins. 79, pp. 287-300. DOI:10.1111/j.1539-6975.2011.01422.x

Cavicchioli, D., Bertoni, D., Pretolani, R., 2018. Farm succession at a crossroads: The interaction among farm characteristics, labour market conditions, and gender and birth order effects. J. Rural Stud. 61, pp. 73-83. DOI:https://doi.org/10.1016/j.jrurstud.2018.06.002

Chavas, J.-P. and Nauges, C., 2020. Uncertainty, Learning, and Technology Adoption in Agriculture. Appl. Econ. Perspect. Policy 42, pp. 42-53. DOI:10.1002/aepp.13003

Crane, T.A., Roncoli, C., Hoogenboom, G., 2011. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. NJAS-Wagen. J. Life. Sc. 57, pp. 179-185. DOI:https://doi.org/10.1016/j.njas.2010.11.002

CSIRO, 2012. Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South-Eastern Australian Climate initiative (SEACI). Commonwealth Scientific and Industrial Research Organisation, Caberra.

Daghagh Yazd, S., Wheeler, S.A., Zuo, A., 2019. Exploring the Drivers of Irrigator Mental Health in the Murray–Darling Basin, Australia. Sustainability 11, pp. 6097.

de Roest, K., Ferrari, P., Knickel, K., 2018. Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. J. Rural Stud. 59, pp. 222-231. DOI:https://doi.org/10.1016/j.jrurstud.2017.04.013

Deressa, T.T., Hassan, R.M., Ringler, C., Alemu, T., Yesuf, M., 2009. Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. Glob. Environ. Change 19, pp. 248-255. DOI:http://dx.doi.org/10.1016/j.gloenvcha.2009.01.002

Dinh, H., Daly, A., Freyens, B., 2017. Farm adjustment strategies to water-related challenges in the Murray-Darling Basin. Pol. Stud. 38, pp. 482-501. DOI:10.1080/01442872.2016.1194386

Ellis, F., 2000. Rural livelihoods and diversity in developing countries. Oxford University Press, New York.

Fankhauser, S., Smith, J.B., Tol, R.S., 1999. Weathering climate change: some simple rules to guide adaptation decisions. Ecolog. Econ. 30, pp. 67-78.

Feola, G., Lerner, A.M., Jain, M., Montefrio, M.J.F., Nicholas, K.A., 2015. Researching farmer behaviour in climate change adaptation and sustainable agriculture: Lessons learned from five case studies. J. Rural Stud. 39, pp. 74-84. DOI:https://doi.org/10.1016/j.jrurstud.2015.03.009

Fuessel, H.-M. and Klein, R.J.T., 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. Clim. Change 75, pp. 301-329. DOI:10.1007/s10584-006-0329-3

Gandure, S., Walker, S., Botha, J.J., 2013. Farmers' perceptions of adaptation to climate change and water stress in a South African rural community. Environ. Dev. 5, pp. 39-53. DOI:http://dx.doi.org/10.1016/j.envdev.2012.11.004

Ghadim, A.K.A., Pannell, D., Burton, M.P., 2005. Risk, uncertainty, and learning in adoption of a crop innovation. Agric. Econ. 33, pp. 1-9. DOI:10.1111/j.1574-0862.2005.00433.x

Grafton, Q.R. and Wheeler, S.A., 2018. Economics of Water Recovery in the Murray-Darling Basin, Australia. Annu. Rev. Resour. Econ. 10, pp. 487-510. DOI:10.1146/annurev-resource-100517-023039

Haensch, J., Wheeler, S.A., Zuo, A., 2019. Do neighbors influence irrigators’ permanent water selling decisions in Australia? J. Hydrol. 572, pp. 732-744. DOI:https://doi.org/10.1016/j.jhydrol.2019.03.023

Hardaker, J.B., 2015. Coping with Risk in Agriculture: Applied Decision Analysis, Coping with Risk in Agriculture. CABI, Wallingford.

Hoffmann, V.H., Sprengel, D.C., Ziegler, A., Kolb, M., Abegg, B., 2009. Determinants of corporate adaptation to climate change in winter tourism: An econometric analysis. Glob. Environ. Change 19, pp. 256-264. DOI:https://doi.org/10.1016/j.gloenvcha.2008.12.002

Hogan, A., Berry, H.L., Ng Peng, S., Bode, A., 2011. Decisions Made by Farmers that Relate to Climate Change. Rural Industries Research and Development Corporation, Canberra.

IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change, Geneva.

Jianjun, J., Wang, X., Yiwei, G., 2015. Gender differences in farmers' responses to climate change adaptation in Yongqiao District, China. Sci. Total Environ. 538, pp. 942-948. DOI:http://dx.doi.org/10.1016/j.scitotenv.2015.07.027

Kassie, M., Teklewold, H., Jaleta, M., Marenya, P., Erenstein, O., 2015. Understanding the adoption of a portfolio of sustainable intensification practices in eastern and southern Africa. Land Use Policy 42, pp. 400-411. DOI:10.1016/j.landusepol.2014.08.016

Kirby, M., Bark, R., Connor, J., Qureshi, M.E., Keyworth, S., 2014. Sustainable irrigation: How did irrigated agriculture in Australia's Murray–Darling Basin adapt in the Millennium Drought? Agric. Water Manag. 145, pp. 154-162. DOI:https://doi.org/10.1016/j.agwat.2014.02.013

Kirby, M., Connor, J., Ahmad, M.-u.D., Gao, L., Mainuddin, M., 2015. Irrigator and Environmental Water Management Adaptation to Climate Change and Water Reallocation in the Murray–Darling Basin. Water Econ. Policy 1, pp. 1-31.

Lee, L., Ancev, T., Vervoort, W., 2012. Evaluation of environmental policies targeting irrigated agriculture: The case of the Mooki catchment, Australia. Agric. Water Manag. 109, pp. 107-116. DOI:https://doi.org/10.1016/j.agwat.2012.02.011

Leonard, B., Kinsella, A., O'Donoghue, C., Farrell, M., Mahon, M., 2017. Policy drivers of farm succession and inheritance. Land Use Policy 61, pp. 147-159. DOI:https://doi.org/10.1016/j.landusepol.2016.09.006

Li, S., Juhász-Horváth, L., Harrison, P.A., Pintér, L., Rounsevell, M.D.A., 2017. Relating farmer's perceptions of climate change risk to adaptation behaviour in Hungary. J. Environ. Manage. 185, pp. 21-30. DOI:http://dx.doi.org/10.1016/j.jenvman.2016.10.051

Lobley, M., Baker, J.R., Whitehead, I., 2010. Farm Succession and Retirement: Some International Comparisons. Journal of Agriculture, Food Systems, and Community Development 1. DOI:10.5304/jafscd.2010.011.009

Loch, A., Bjornlund, H., Wheeler, S.A., Connor, J., 2012. Allocation trade in Australia: a qualitative understanding of irrigator motives and behaviour. Australian J. Agr. Resource Econ. 56, pp. 42-60. DOI:https://doi.org/10.1111/j.1467-8489.2011.00575.x

Loch, A., Adamson, D., Auricht, C., 2019. (g)etting to the point: The problem with water risk and uncertainty. Water Resour. Econ.pp. 100154. DOI:https://doi.org/10.1016/j.wre.2019.100154

MDBA, 2016. Murray–Darling Basin Boundary map. Murray-Darling Basin Authority, Canberra.

Mishra, A.K. and Goodwin, B.K., 2006. Revenue insurance purchase decisions of farmers. Appl. Econ. 38, pp. 149-159. DOI:10.1080/00036840500367724

Moniruzzaman, S., 2015. Crop choice as climate change adaptation: Evidence from Bangladesh. Ecolog. Econ. 118, pp. 90-98. DOI:http://dx.doi.org/10.1016/j.ecolecon.2015.07.012

Morris, W., Henley, A., Dowell, D., 2017. Farm diversification, entrepreneurship and technology adoption: Analysis of upland farmers in Wales. J. Rural Stud. 53, pp. 132-143. DOI:https://doi.org/10.1016/j.jrurstud.2017.05.014

Morrison, M., Oczkowski, E., Greig, J., 2011. The primacy of human capital and social capital in influencing landholders' participation in programmes designed to improve environmental outcomes. Australian J. Agr. Resource Econ. 55, pp. 560-578. DOI:10.1111/j.1467-8489.2011.00554.x

Nadolnyak, D., Vedenov, D., Novak, J., 2008. Information Value of Climate-Based Yield Forecasts in Selecting Optimal Crop Insurance Coverage. Amer. J. Agr. Econ. 90, pp. 1248-1255. DOI:10.1111/j.1467-8276.2008.01212.x

Nauges, C., Wheeler, S.A., Zuo, A., 2016. Elicitation of irrigators' risk preferences from observed behaviour. Australian J. Agr. Resource Econ. 60, pp. 442-458.

Nauges, C. and Wheeler, S.A., 2017. The Complex Relationship Between Households' Climate Change Concerns and Their Water and Energy Mitigation Behaviour. Ecolog. Econ. 141, pp. 87-94. DOI:https://doi.org/10.1016/j.ecolecon.2017.05.026

Neset, T.-S., Asplund, T., Käyhkö, J., Juhola, S., 2019. Making sense of maladaptation: Nordic agriculture stakeholders’ perspectives. Clim. Change 153, pp. 107-121. DOI:10.1007/s10584-019-02391-z

Ng’ang’a, S.K., Van Wijk, M.T., Rufino, M.C., Giller, K.E., 2016. Adaptation of agriculture to climate change in semi-arid Borena, Ethiopia. Reg. Environ. Change 16, pp. 2317-2330. DOI:10.1007/s10113-016-0940-4

Nicholas, K.A. and Durham, W.H., 2012. Farm-scale adaptation and vulnerability to environmental stresses: Insights from winegrowing in Northern California. Glob. Environ. Change 22, pp. 483-494. DOI:http://dx.doi.org/10.1016/j.gloenvcha.2012.01.001

Pannell, D., Marshall, G.R., Barr, N., Curtis, A., Vanclay, F., Wilkinson, R., 2006. Understanding and promoting adoption of conservation practices by rural landholders. Aust. J. Exp. Agric. 46, pp. 1407-1424. DOI:https://doi.org/10.1071/EA05037

Park, S.E., Marshall, N.A., Jakku, E., Dowd, A.M., Howden, S.M., Mendham, E., Fleming, A., 2012. Informing adaptation responses to climate change through theories of transformation. Glob. Environ. Change 22, pp. 115-126. DOI:http://dx.doi.org/10.1016/j.gloenvcha.2011.10.003

Quiggin, J., Adamson, D., Chambers, S., Schrobback, P., 2010. Climate change, uncertainty, and adaptation: the case of irrigated agriculture in the Murray–Darling Basin in Australia. Can. J. Agr. Econ. 58, pp. 531-554.

Qureshi, E. and Whitten, S.M., 2014. Regional impact of climate variability and adaptation options in the southern Murray–Darling Basin, Australia. Water Resour. Econ. 5, pp. 67-84. DOI:https://doi.org/10.1016/j.wre.2013.12.002

Roco, L., Engler, A., Bravo-Ureta, B., Jara-Rojas, R., 2014. Farm level adaptation decisions to face climatic change and variability: Evidence from Central Chile. Environ. Sci. Policy 44, pp. 86-96. DOI:http://dx.doi.org/10.1016/j.envsci.2014.07.008

Seidl, C., 2020. Understanding adaptation and water market behaviour of irrigators and non-landholder stakeholders in the Murray-Darling Basin. PhD Thesis, University of Adelaide, Adelaide, 315 pp.

Seidl, C., Wheeler, S.A., Zuo, A., 2020. Treating water markets like stock markets: Key water market reform lessons in the Murray-Darling Basin. J. Hydrol. 581, pp. 124399. DOI:https://doi.org/10.1016/j.jhydrol.2019.124399

Sherrick, B.J., Barry, P.J., Ellinger, P.N., Schnitkey, G.D., 2004. Factors Influencing Farmers' Crop Insurance Decisions. Amer. J. Agr. Econ. 86, pp. 103-114. DOI:10.1111/j.0092-5853.2004.00565.x

Simtowe, F. and Mausch, K., 2019. Who is quitting? An analysis of the dis-adoption of climate smart sorghum varieties in Tanzania. Int. J. Clim. Chang. Str. 11, pp. 341-357. DOI:10.1108/ijccsm-01-2018-0007

Smit, B. and Skinner, M.W., 2002. Adaptation options in agriculture to climate change: a typology. Mitig. Adapt. Strateg. Glob. Chang. 7, pp. 85-114.

Tambo, J.A., 2016. Adaptation and resilience to climate change and variability in north-east Ghana. Int. J. Disast. Risk Re. 17, pp. 85-94. DOI:http://dx.doi.org/10.1016/j.ijdrr.2016.04.005

Ticehurst, J.L. and Curtis, A.L., 2015. Can existing practices expected to lead to improved on-farm water use efficiency enable irrigators to effectively respond to reduced water entitlements in the Murray–Darling Basin? J. Hydrol. 528, pp. 613-620. DOI:https://doi.org/10.1016/j.jhydrol.2015.06.055

Ticehurst, J.L. and Curtis, A.L., 2018. The intention of irrigators to adopt water use efficient measures: case studies in the north and south of the Murray–Darling Basin. Australas. J. Water Resour. 22, pp. 149-161. DOI:10.1080/13241583.2018.1486267

Touch, V., Martin, R.J., Scott, J.F., Cowie, A., Liu, D.L., 2016. Climate change adaptation options in rainfed upland cropping systems in the wet tropics: A case study of smallholder farms in North-West Cambodia. J. Environ. Manage. 182, pp. 238-246. DOI:http://dx.doi.org/10.1016/j.jenvman.2016.07.039

van der Linden, S., 2017. Determinants and Measurement of Climate Change Risk Perception, Worry, and Concern., Oxford Research Encyclopedia of Climate Science. Oxford University Press, New York.

Vigani, M. and Kathage, J., 2019. To Risk or Not to Risk? Risk Management and Farm Productivity. Amer. J. Agr. Econ. 101, pp. 1432-1454. DOI:10.1093/ajae/aaz020

Wang, J., Klein, K.K., Bjornlund, H., Zhang, L., Zhang, W., 2015. Adoption of improved irrigation scheduling methods in Alberta: An empirical analysis. Can. Water Resour. J. 40, pp. 47-61. DOI:10.1080/07011784.2014.975748

WEF, 2019. The Global Risks Report 2019. World Economic Forum, Geneva.

Wheeler, S.A., Bjornlund, H., Zuo, A., Edwards, J., 2012. Handing down the farm? The increasing uncertainty of irrigated farm succession in Australia. J. Rural Stud. 28, pp. 266-275.

Wheeler, S.A. and Cheesman, J., 2013. Key findings from a survey of sellers to the restoring the balance programme. Econ. Pap. 32, pp. 340-352. DOI:https://doi.org/10.1111/1759-3441.12038

Wheeler, S.A., Zuo, A., Bjornlund, H., 2013. Farmers' climate change beliefs and adaptation strategies for a water scarce future in Australia. Glob. Environ. Change 23, pp. 537-547.

Wheeler, S.A. and Zuo, A., 2017. The impact of drought and water scarcity on irrigator farm exit intentions in the Murray–Darling Basin. Australian J. Agr. Resource Econ. 61, pp. 404-421. DOI:doi:10.1111/1467-8489.12218

Wheeler, S.A., Zuo, A., Bjornlund, H., Mdemu, M.V., van Rooyen, A., Munguambe, P., 2017. An overview of extension use in irrigated agriculture and case studies in south-eastern Africa. Int. J. Water Resour. D. 33, pp. 755-769. DOI:10.1080/07900627.2016.1225570

Wheeler, S.A., Zuo, A., Loch, A., 2018. Water torture: Unravelling the psychological distress of irrigators in Australia. J. Rural Stud. 62, pp. 183-194. DOI:https://doi.org/10.1016/j.jrurstud.2018.08.006

Wheeler, S.A. and Marning, A., 2019. Turning water into wine: Exploring water security perceptions and adaptation behaviour amongst conventional, organic and biodynamic grape growers. Land Use Policy 82, pp. 528-537. DOI:https://doi.org/10.1016/j.landusepol.2018.12.034

Wheeler, S.A., Carmody, E., Grafton, Q.R., Kingsford, R.T., Zuo, A., 2020a. The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. Resour. Conserv. Recycl. 159, pp. 104755. DOI:10.1016/j.resconrec.2020.104755

Wheeler, S.A., Xu, Y., Zuo, A., 2020b. Modelling the climate, water and socio-economic drivers of farmer exit in the Murray-Darling Basin. Clim. Change 158, pp. 551-574. DOI:10.1007/s10584-019-02601-8

Wooldridge, J.M., 2010. Econometric analysis of cross section and panel data. MIT press, London.

Wooldridge, J.M., 2015. Control function methods in applied econometrics. J. Human Res. 50, pp. 420-445. DOI:10.3368/jhr.50.2.420

Zellner, A., 1963. Estimators for seemingly unrelated regression equations: Some exact finite sample results. J Am Stat Assoc 58, pp. 977-992. DOI:https://doi.org/10.1080/01621459.1963.10480681

Zilberman, D., Zhao, J., Heiman, A., 2012. Adoption versus adaptation, with emphasis on climate change. Annu. Rev. Resour. Econ. 4, pp. 27-53. DOI:10.1146/annurev-resource-083110-115954

Zuo, A., Nauges, C., Wheeler, S.A., 2015a. Farmers' exposure to risk and their temporary water trading. Europ. Rev. Agr. Econ. 42, pp. 1-24. DOI:10.1093/erae/jbu003

Zuo, A., Wheeler, S.A., Boxall, P., Adamowicz, W.L., Hatton MacDonald, D., 2015b. Identifying Water Prices at which Australian Farmers Will Exit Irrigation: Results of a Stated Preference Survey. Econ. Rec. 91, pp. 109-123. DOI:10.1111/1475-4932.12186

Zuo, A., Wheeler, S.A., Adamowicz, W.L., Boxall, P.C., Hatton-MacDonald, D., 2016. Measuring Price Elasticities of Demand and Supply of Water Entitlements Based on

Stated and Revealed Preference Data. Amer. J. Agr. Econ. 98, pp. 314-332. DOI:10.1093/ajae/aav022

Appendix A

Table A1 Overview of common adaptation strategy categories

Dimension of interest	Adaptation category	Definition and source	Example
Adapting actor	Autonomous/unintentional	Natural spontaneous adjustment undertaken by independent actors	Changed harvesting schedule
	Planned/purposeful	Conscious adjustment/intervention requiring coordination with others (Smit and Skinner, 2002)	Investment in irrigation infrastructure
Adaptation intent	Facilitating	Enhances actors’ ability to adapt	Research developing drought resistant crops
	Implemented	Directly reduce actors’ exposure or sensitivity to uncertainty (Fuessel and Klein, 2006)	Crop/yield insurance
Adaptation scale	Micro level	Small-scale	Irrigation scheduling by individual farmer/plot
	Macro level	Large-scale (Zilberman et al., 2012)	No-tillage agriculture across region
	Global	Global scale	New global production standards
	Local	Local scale (Brooks and Adger, 2005)	Solar-powered irrigation system
	Incremental	Uses existing technologies and institutional frameworks	Fodder substitution for irrigating pasture
	Transformative	Major change in resource allocation across temporal and spatial scales (Park et al., 2012)	Dryland to irrigated agriculture
Adaptation duration	Short-term/tactical	Provides short-term adaptation benefits	Fodder substitution
	Long-term/strategic	Provides long-term adaptation benefits (Smit and Skinner, 2002)	Upgrading to drip irrigation
Adaptation timing	Reactive	The response to the impacts of change/uncertainty after they materialised	Relocation after flood/bush fire
	Anticipatory	Anticipates future and seeks to address changes before they materialise (Fankhauser et al., 1999)	Farm/crop insurance
Adaptation technology	Hard	Tangible and mechanised, similar to hard technology	Irrigation infrastructure
	Soft	Change of management and skills, often intangible, similar to soft technology (Wheeler et al., 2017)	Change of planting dates
Influence on size/structure of adapting actor	Expansive and Accommodating	Designed to expands efforts and production, or accommodate change in existing size or structure	Increased water ownership, change in soil management practices
	Contractive	Designed to reduce effort, resource ownership and size (Wheeler et al., 2013)	Sale of land in change-affected areas
General	Technological development	Research and development of new technologies or managerial innovations	Weather and climate information systems
	Government programs and insurance	Government assistance or incentive programs, insurances against different uncertainties	Agricultural support programs and subsidies
	Farm financial management	Various financial tools and management practices	Income diversification
	Farm production practices	Changing farm production systems to better cope with uncertainty (Smit and Skinner, 2002)	Crop diversification

Table A2 Overview of different capitals and their impact on adaptation in the agricultural economics and climate change adaptation literature

Type of capital	Description	Common examples	Influence on Adaptation	How often studied	Selected sources
Financial capital	Economic characteristics of the actor's enterprise	Access to credit	(+)	Occasionally	(Deressa et al., 2009; Touch et al., 2016)
		Debt	Unclear	Rarely	(Wheeler et al., 2013)
		Income/wealth	(+)	Often	(Below et al., 2012; Li et al., 2017)
		Off-farm income	Unclear	Occasionally	(Deressa et al., 2009; Wang et al., 2015)
Human capital	Characteristics of the actor	Age	Usually (-)	Occasionally	(Pannell et al., 2006; Roco et al., 2014)
		Climate change belief	Usually (+)	Rarely	(Deressa et al., 2009; Tambo, 2016)
		Climate change risk perception	Usually (+)	Rarely	(Alam, 2015; Jianjun et al., 2015)
		Education	Usually (+)	Often	(Alam, 2015; Abid et al., 2016)
		Farm experience	Usually (+)	Occasionally	(Alam, 2015; Abid et al., 2016)
		Female gender	Usually (-)	Occasionally	(Below et al., 2012; Jianjun et al., 2015)
		Health	(+)	Rarely	(Wheeler et al., 2013)
		Household size	Usually (+)	Occasionally	(Bryan et al., 2013)
		Past experience	(+)	Rarely	(Ghadim et al., 2005; Nicholas and Durham, 2012)
		Risk preference/aversion	Unclear	Rarely	(Ghadim et al., 2005; Tambo, 2016)
		Farm succession	(+)	Rarely	(Li et al., 2017)
Natural capital	Environmental characteristics	Rainfall	Usually (-)	Occasionally	(Deressa et al., 2009; Gandure et al., 2013)
		Region	Unclear	Occasionally	(Abid et al., 2016; Li et al., 2017)
		Soil quality	Usually (-)	Occasionally	(Gandure et al., 2013; Touch et al., 2016)
		Temperature	(+)	Occasionally	(Deressa et al., 2009; Gandure et al., 2013)
Physical capital	Technology and characteristics of production	Farm size	Usually (+)	Often	(Ghadim et al., 2005; Li et al., 2017)
		Farm technology/inventory	Usually (+)	Occasionally	(Bryan et al., 2013)
		Tenure	Unclear	Occasionally	(Abid et al., 2016; Li et al., 2017)
Social capital	Characteristics of the actor's social unit	Extension services	(+)	Occasionally	(Bryan et al., 2013; Li et al., 2017)
		Government programs and subsidies	Usually (+)	Rarely	(Bryan et al., 2013; Gandure et al., 2013)
		Membership of social networks	Usually (+)	Occasionally	(Below et al., 2012; Li et al., 2017)

Table A3 Independent variable definitions and summary statistics by capital types, based on survey (n=1000) and Bureau of Meteorology (BOM) data

Capital	Variable definition	Data source	Mean (std. dev.)	Min	Max
Financial capital	Farm debt (in $m) [1]	Irrigator survey (n=1000)	0.4(0.5)	0	1.25
	Farmland value (in $m) [1]		1.4(1.0)	0.125	3
	Net farm income (in $m) [1]		0.1(0.1)	0	0.25
	Number of insurance contracts [2]		4.6(1.4)	0	7
	Off-farm income (in %)		24.8(31.1)	0	100
	Productivity change (last 5 years: 1=strongly decreasing; 5=strongly increasing)		3.2(1.2)	1	5
Human capital	Believes climate change is a risk for their region (1= yes, 0 = otherwise)	Irrigator survey (n=1000)	0.4(0.5)	0	1
	Irrigator's age (in years)		58.7(11.4)	24	90
	Low education (1 = highest education level is year 10 or below, 0 = otherwise)		0.2(0.4)	0	1
	Male gender (1=male, 0=otherwise)		0.9(0.3)	0	1
	Plans for climate change on their farm (1= yes, 0= otherwise)		0.5(0.5)	0	1
	Succession plan (1 = successor nominated, 0=otherwise)		0.4(0.5)	0	1
	Whole of farm plan (1= has a farm plan, 0=otherwise)		0.7(0.4)	0	1
Natural capital	Average final water allocation last 10 years (in %) [3]	BOM-specialised request	0.58(0.26)	0	0.96
	Net rainfall over last 10 years (average of annual rainfall minus evaporation, in mm) [4]		-1333.7(282.6)	-1943.1	-207.3
	Temperature variability over last 30 years (std. dev. of temperature in °C) [4]		0.75(0.07)	0.53	0.83
	State dummy VIC (1 = yes; 0 = otherwise) [5]	Irrigator survey (n=1000)	0.21(0.41)	0	1
	State dummy SA (1 = yes; 0 = otherwise) [5]		0.37(0.48)	0	1
Physical capital	Carry-over use between 2014-2016 (1= used carry-over, 0= otherwise)	Irrigator survey (n=1000)	0.6(0.5)	0	1
	Farm size (irrigated plus dryland; in 100ha)		9.0(27.3)	0	368
	Industry: Broadacre (1= main income from broadacre, 0= otherwise) [6]		0.3(0.4)	0	1
	Industry: Dairy (1= main income from dairy, 0= otherwise) [6]		0.2(0.4)	0	1
	Industry: Livestock (1= main income from livestock, 0 = otherwise) [6]		0.2(0.4)	0	1
	Majority of irrigated farm area under drainage (1= drainage on more than 50%, 0= otherwise)		0.6(0.5)	0	1
	Majority of irrigated farm area under drip irrigation (1= drip irrigation on more than 50%, 0= otherwise)		0.2(0.4)	0	1
	Number of employees		2.6(3.4)	1	60
	Owns excess water entitlements (1= owns more water then needed, 0= otherwise)		0.2(0.4)	0	1
	Water application rate (ML/irrigated ha)		11.3(179.0)	0	5634
	Water ownership size (Ln of long-term annual average yield (LTAAY) of water entitlements) [7]		5.3(1.8)	0	10.3
Social capital	Social group membership (1= member in any group; 0=otherwise)	Irrigator survey (n=1000)	0.6(0.5)	0	1
Past behaviour	Expansive adaptation strategies used last 5 years	Irrigator survey (n=1000)	2.1(1.5)	0	6
	Accommodating adaptation strategies used last 5 years		2.0(1.5)	0	7
	Contractive adaptation strategies used last 5 years		1.1(1.0)	0	4

Note: [1] Net farm income, debt and farmland value figures were semi-continuous variables.

[2] Includes crop insurance, private health cover, home and content insurance, live insurance, car insurance, work cover and income protection.

[3] Allocation factor is the seasonal amount of water received as a percentage of nominal water entitlements based on security and location.

[4] Rainfall, evaporation, and temperature data over 30-year period (1986–2015). No significant difference between 10- and 30-year net rainfall, temperature variability over 30 years provides better model fit.

[5] Irrigators in New South Wales acted as the reference group

[6] Horticulture industry acted as the reference group.

[7] LTAAY is the long-term annual average volume of water permitted to be taken for consumptive use under a water access entitlement. Currently all LTAAY figures are calculated using the long-term diversion limit equivalent factors, with these factors to be accredited in finalised state water resource plans (Wheeler et al., 2020a).