Adaptation responses to increasing drought frequency*

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Using state contingent analysis, we discuss how and why irrigators adapt to alternative water supply signals. Focusing on the timing of water allocations, we explore inherent differences in the demand for water by two key irrigation sectors: annual and perennial producers. The analysis explores the reliability of alternative water property right bundles and how reduced allocations across time influence alternative responses by producers. Our findings are then extended to explore how management strategies could adapt to two possible future drier state types: (i) where an average reduction in water supply is experienced; and (ii) where drought becomes more frequent. The combination of these findings is subsequently used to discuss the role water reform policy plays in dealing with current and future climate scenarios.

Key words: drought, property rights, state-contingent analysis, water-use adaptation.

1. Introduction

Water is a finite and often scarce resource with many competing uses. Efforts to allocate these scarce supplies to meet rising demands from the urban, agricultural and environmental sectors pose a significant policy challenge, especially when equity issues and how allocations may disadvantage vulnerable communities are considered (World Economic Forum 2015). Current global assessments predict that demand for potable supplies will surpass current developed supply by 2050, and that climate change may exacerbate this gap (WWAP 2014). While the inherent variability of current rainfall is a binding factor of natural fresh water supplies, climate change is expected to aggravate the relative scarcity of fresh water supplies for many countries by 2050; both in terms of average water supply and the frequency and magnitude of extreme weather events (e.g. droughts and floods) (Adamson *et al.* 2009). These supply and variability changes add new complexities for water managers.

Australia's agricultural production is especially susceptible to rainfall variability (Anderson 1979). In the country's south-east where the majority of irrigated agriculture is located, reduced rainfall, higher temperatures and increased frequency/intensity of droughts are projected to stress available water resources and intensify water competition (MSSI 2015). While Australian native vegetation, ecosystems (Cleverly *et al.* 2016) and farmers (Adamson *et al.* 2009) have adapted to existing rainfall variation, climate change adds new dimensions requiring further adaptation that may be constrained by biophysical and policy factors (Loch *et al.* 2014a). By 2050, altered rainfall patterns and more frequent/longer droughts are expected to negatively affect current commercial production varietals.

Faced with these risks, producers must assess whether altering current input/output sets in response to possible future climate states will enhance their long-run competitive advantage for both expected new normal and extreme water supply outcomes. Further, policy supporting agricultural sector climate change resilience must avoid poorly designed strategies that increase producer vulnerability in the face of drought. Efforts to explore the nature of uncertainty surrounding adaptation can aid in the development of policy that allows producers to respond to the real costs and benefits of risk-taking (OECD 2016). Indeed, in-depth explorations of such uncertainty should inform policy of the benefits from flexible water reallocation programmes/ rules to both irrigated agriculture and society in general (Loch *et al.* 2014a,b). With a future that portends more frequent and extreme drought events, an understanding of the trade-offs and consequences from management responses becomes even more valuable. For example, the 1992 Australian *National Drought Policy* requires producers to assume greater responsibility for managing risks associated with climatic variability. A key future drought policy issue therefore will be how to assist producers in dealing with water scarcity effects while maintaining incentives for them to prepare appropriately for more frequent and lengthy droughts (Quiggin and Chambers 2006).

One suggested approach is for producers to increase their adoption of irrigation efficiency and water-saving farm practices to balance the aggregate supply/demand for water (OECD 2016). Increased irrigation efficiency is a current basis for large-scale on-farm (e.g. shifting from flood to drip irrigation methods) and off-farm (e.g. lining irrigation supply channels) investment to mitigate risk and recover water resources for the environment in Australia's Murray-Darling Basin (MDB) (Loch *et al.* 2014b). However, a growing literature suggests that increased irrigation efficiency may drive perverse outcomes such as increased consumption (Ward and Pulido-Velazquez 2008), and producers may be advantaged by managing soil–water rather than investing in infrastructure (Wheeler *et al.* 2015). While these investments increase net returns, they decrease total productivity (O'Donnell 2010) and encourage investment patterns that are not resilient to droughts (Gómez and Pérez-Blanco 2014). Adamson and Loch (2014) noted that irrigation technology subsidy programmes lock water entitlements (rights) into existing

areas of low economic return and are inefficient for dealing with inequitable water shares. They degrade water quality as this approach misinterprets the value of irrigation return flows and rebound effects increase the area under irrigation. To be efficient, irrigators must manage their exposure to the risks associated with variable water allocation (Khan *et al.* 2010) and understand the limitations of adopting production systems that encourage flat payoff functions (Pannell 2006). Our study therefore examines producer responses to more frequent drought outcomes, particularly in regard to water supply changes and in the context of current policy signals supporting adoption of more efficient irrigation technology. We also identify if these investment signals could drive producers to less heterogeneous production systems over time, perhaps in line with reactive calls to reduce production of 'thirsty' crops such as cotton and rice during drought conditions. Finally, we test whether such homogenous production systems ultimately entail riskier adaptation options under future increased drought frequency scenarios.

2. Literature

There is a significant and growing literature investigating the impacts of climate on irrigated agriculture, particularly with respect to the role uncertainty plays in influencing grower adaptation and response (Hurd 2015). One observation from surveying this literature is the importance of both intensive (e.g. changing applied water rates) and extensive (e.g. crop mix and irrigated area) producer adaptation (Schwabe and Connor 2012); and that failure to account for both responses in models will lead to overestimates of the costs of climate change. A second observation is that producer decisions are made under uncertainty about what the future holds with respect to climate, weather and subsequent water supply allocations. Overlooking these conditions likely limits our ability to inform policy on matters related to risk (Just and Pope 2003). In response, Chavas *et al.* (2010) suggest that state-contingent analysis (SCA) provides insights into decision-making under risk and uncertainty.

State-contingent analysis representing a decision maker's resource (re) allocation or trade-off requirement by type, place, date and state of nature (e.g. water supply quantity in drought years) provides insight into the consequences of policy (Rasmussen 2003). Although pioneered by Arrow and Debreu (1954), state contingent analyses of producer responses to Australian water scarcity have only occurred relatively recently. Adamson *et al.* (2007) discuss irrigation water quantity subject to climatic and policy uncertainty through the SCA lens. They examine irrigation investment to drought-proof MDB agriculture and offer a decision framework suitable for policy analysis of strategic issues related to long-term producer investment choices within an uncertain set of state variables. Connor *et al.* (2009) model increasing drought severity and salinity impacts on water quality as drivers of production shifts in the Lower Murray using a mathematical programming model comprised of

states of nature. Although the model does not (re)allocate resources over time, the authors identify risks associated with increased technology investment during severe drought states, and a return to (less risky) annual production systems where drought is prolonged and salinity effects become pronounced. Adamson *et al.* (2009) use SCA to examine the effects on MDB system water inflows from climate change, and potential increasing frequency of drought event effects on reallocating inputs. Finally, Loch and Adamson (2015) use SCA to identify possible land-use and water-use rebound effects from investment policy signals, while Adamson and Loch (under review) use SCA to discuss externality impacts across a range of parties from possible unintended outcomes from irrigation efficiency investment programmes. This article contributes to the literature by using an SCA framework to analyse and describe how irrigators respond and adapt to increased drought frequency, where new state spaces and natures are being realised.

In the SCA, nature is the term used to describe the state-space $S \in \Omega$ under uncertainty, providing an exhaustive set of mutually exclusive events that describe all of the salient features of the uncertainty in question. So when the final state s is revealed, all ambiguity is removed allowing for the traditional approaches used to solve certainty to be applied. Critically, a producer has *no ability to control* which state of nature is realised. Once s occurs, they must adopt specific s-based strategies to maximise their objective function. Alternatively, no matter the action undertaken by a producer in a preceding state of nature, the next realised state will be independent of their action(s). However, the producer's action in any prior state will leave a legacy (negative or positive) to which they may need to adapt once the final state is revealed. Thus, in SCA models output uncertainty results from producer choices: they can stabilise (homogenise) production over time, though the long-run costs of that choice may be high (Chambers and Quiggin 2000).

3. Methodology

Our analysis employs a SCA framework to analyse and describe more frequent drought adaptation outcomes in response to current policy signals based largely on the concepts detailed in Quiggin and Chambers (2004). That paper describes SCA's development from Ricardian standard two-output technology frontier curves, through Fisher's (1930) elegant solution to the problem of incorporating intertemporal production, consumption and borrowing, to finally arrive at Arrow (1953) and Debreu's (1959) tractable model of stochastic production functions and production frontier choices under uncertainty.

3.1 State-contingent technology

We define SCA drawing on Chambers and Quiggin (2000). The state-space $S \in \Omega$ provides mutually exclusive events (a state of nature s) that describe all

the salient features of uncertainty. When s is revealed all ambiguity is removed, allowing for applications of traditional approaches used to solve certainty. Once s occurs, decision makers must also adopt specific s-based strategies to maximise their objective function. Recall that the s-based strategies adopted in a preceding state of nature are independent of the next realised state, and may leave a legacy (negative or positive) requiring further adaptation once the new s is realised.

As SCA deals with production under uncertainty, the total size of the state space can be kept small, and similar states with identical management actions condensed. Yields, prices and costs outcomes from realised states are not states themselves. State-contingent production is then defined as:

$$z_s = f_s(x, \varepsilon) s \in \Omega = \{1, \ldots, S\},$$

where output z in state s is dependent on the availability of input x in s and any associated variation ε in that s. Thus, state-contingent technology can be represented by a continuous input correspondence $X : \Re_+^S \to \Re_+^N$, which maps state-contingent outputs onto input sets capable of producing that state-contingent output vector, so that:

$$X(\mathbf{z}) = \{x \in \Re_+^N : \mathbf{x} \text{ can produce } \mathbf{z}\}.$$

The properties of the state-contingent technology, input and output sets are as follows. Output sets have: (i) defined upper and lower bounds so that $X(z)$ is closed for all $\Re_+^S$ and production of z from x is finite; (ii) the decision maker can decide not to respond, but costs are still incurred to obtain a positive output so that $X(0_s) = \Re_+^N$ (no fixed costs), and $0_N \notin X(z)$ for $z \geq 0_s$ and $z \neq 0_s$ (no free lunch); (iii) there is free disposability of state-contingent outputs where $z' \leq z \Rightarrow X(z) \subset X(z')$; and (iv) non-negative marginal productivity exists where $x' \geq x \in X(z) \Rightarrow x' \in X(z)$. The use of inputs is determined by the cost function, where of cost of x is $\mathbf{w}$ as follows:

$$c(\mathbf{w}, \mathbf{z}) = \min_x \{\mathbf{w}\mathbf{x} : \mathbf{x} \in \mathbf{X}(z)\} \mathbf{w} \in \Re_{++}^N.$$

When the input correspondence satisfies properties X, the cost function satisfies the following conditions: (i) input sets have defined upper and lower limits so that $X(\mathbf{z})$ is closed for all $\mathbf{z} \in \Re_+^M$; (ii) $c(\mathbf{w}, \mathbf{z})$ is continuous on $\Re_+^S$ and positively linear, homogeneous, non-decreasing, concave and continuous on $\Re_{++}^N$; (iii) Shephard's lemma applies so that indifference curves are convex allowing for a unique cost minimisation point; (iv) $(\mathbf{w},\mathbf{z}) \geq 0$, $c(\mathbf{w},0_s) = 0$ and $(\mathbf{w},\mathbf{z}) >$ for $\mathbf{z} \geq 0_s$, $\mathbf{z} \neq 0_s$ and $\mathbf{z}^0 \geq \mathbf{z} \Rightarrow c(\mathbf{w}, \mathbf{z})$ provide a complete representation of the cost function; and (v) standard duality theorems apply so that $X(\mathbf{z}) = \cap_{\mathbf{w} > 0}\{\mathbf{x} : \mathbf{w}\mathbf{x} \geq c(\mathbf{w}, \mathbf{x})\}$.

When the first s is realised, a decision-maker will allocate $\mathbf{x}$ vector of inputs $\mathbf{x} = (x_1, \ldots, x_N)$ with corresponding input prices of $\mathbf{w} = (w_1, \ldots, w_N)$, which provides a cost of $c = \mathbf{wx}$. The decision maker's subjective belief about subsequent states of nature is $\boldsymbol{\pi}$, a vector described by $(\boldsymbol{\pi} = \pi_1, \ldots, \pi_s)$. When the subsequent s is revealed, output from allocated inputs and costs are derived from the transformation function of $T(x, z)$; where $\mathbf{z} = (z_1, \ldots, z_s)$ and prices $\mathbf{z}$ are a vector of $\mathbf{p} = (p_1, \ldots, p_s)$. Finally, revenue is described as $\mathbf{r} = (z_1 p_1, \ldots, z_s p_s)$ allowing for net returns to be $\mathbf{y} = (y_1, \ldots y_s) = (z_1 p_1 - wx, \ldots, z_s p_s - wx) = (\mathbf{r} - \mathbf{c})$. To maximise their utility W, a decision-maker thus selects the input bundle $\mathbf{x}$ such that $MaxW[Y] = \sum_{s \in \Omega} \pi(\mathbf{r} - \mathbf{c})$.

3.2 Adaptation to states

In this article, we consider short-run and long-run producer demand for water in response to state-dependent exogenous water input supply, and exogenous policy impacts on subsequent demand and supply curves. Figure 1 provides a simplified description of a producer's demand response to a specified exogenous allocation (supply) of agricultural water. At equilibrium, the supply of water q_w meets the producer's needs; they are willing to pay p_w to access this water, which we assume is represented by unitary demand (i.e. $(E_d) = 1$). When water supply contracts left of q_w, the producer is willing to pay $\geq p_w$ to obtain water. This shows that when water becomes scarce, short-run demand become relatively inelastic (i.e. $0 < E_d < 1$) (e.g. Wheeler *et al.* 2008) as producers attempt to keep commodities alive. Where supply scarcity persists, demand quickly becomes highly inelastic reflecting the general inelastic nature of Australian water markets (Zuo *et al.* 2015). When there is insufficient water, irreversible producer losses occur where either further
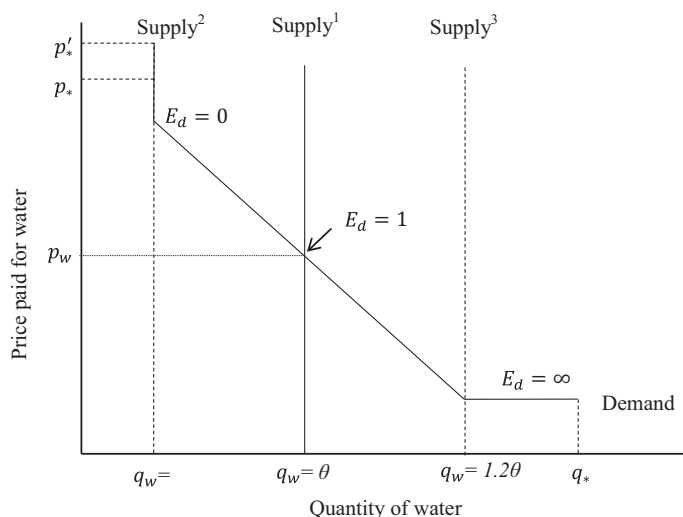

Figure 1 Producer demand response to water supply by state of nature.

supply is partially/completely constrained or where p_w exceeds a producer's capacity to pay above a long-run choke price (Olmstead and Stavins 2007). We employ both long-p_* and short-run p'_* choke prices to represent rational decision-making behaviour and the opportunity costs of re-establishing perennial crops. Keeping in mind the inherent endogeneity between water prices and supply/demand (Zuo *et al.* 2015), the choke price p_* is the long-run willingness to pay for water resources. But in the short-run, producers may be willing to pay p'_* to: preserve perennial capital investments; 'finish' a crop where the expected risk of large profit reductions (downside risk) justifies that investment (Zuo *et al.* 2014); or if producers expect next year's water supply will be 'normal'. By way of example, Nauges *et al.* (2016) discuss broadacre producers' ability to smooth profits across drought and non-drought years – options not available to perennial producers – reflected in respective marginal water values (i.e. \$547/megalitre for perennial versus \$61/megalitre for broadacre).

As water supply increases, the value of additional water decreases as it no longer becomes the binding production constraint. Now water can be utilised to expand production into less productive areas, or opportunistically on commodities that provide lower marginal returns per megalitre. Water use will continue until all other resources are utilised and/or the addition of one more unit of water results in a negative payoff. Past Australian water policy has influenced both the long-run demand for, and supply of, water through commodity support and subsidised water infrastructure. Australian producers are risk averse to weather effects such as future drought uncertainty (Nguyen *et al.* 2007). However, Australian agricultural policy and sector support often provides perverse outcomes diminishing self-reliance (Quiggin and Chambers 2004). That said, there are relatively few market-based risk offset options available to Australian producers (Khuu and Juerg Weber 2013). In this context, large-scale Australian producer adoption of subsidised efficient irrigation technology ahead of private investment is provided with additional logic. Subsidising irrigation technology adoption to drought-proof economic activity in the MDB has shifted water supply to the right (Adamson and Loch 2014). Further, as the true cost of developing and supplying water is generally never passed on to those same irrigators, the demand for water also rapidly increases (Davidson 1969). With this framework in mind, we examine the outcome of drought events with an increased frequency.

4. The management response to a given state allocable water allocation

In Australia, policy makers have internalised natural spatial climatic water supply variability through carefully designed water entitlements reflecting resource reliability. Three consumptive water entitlements with declining reliability have emerged: (i) high security; (ii) general security; and (iii) supplementary (low) security entitlements. Actual water quantity received depends on the bundle of water entitlements held and the total water

available to be shared across consumptive property right owners. Supply is affected by endogenous (infrastructure and water management) and exogenous (rainfall states of nature) variables. Exogenous rainfall is uncertain for any future temporal period.

For our model, assume there are three states of nature s: normal ($s1$), drought ($s2$) and wet ($s3$), for which are identified three possible water supply outcomes θ. All values provided herein are for illustrative purposes only. Under a normal state of nature, the long-run average reliability of a user's portfolio of entitlements is represented by $q_w = \theta$. During drought states ($s2$), the producer's entitlements provide 0.6θ, while in wet states ($s3$) increased total supply provides 1.2θ. Figure 1 correlates water supply by state of nature outcome with the price users would be willing to pay for additional water inputs to derive a demand curve. As total supply increases in $s3$, the price will fall to a perfectly elastic state until water is no longer the binding constraint (e.g. where land-limits constrain further water use); at which point its value falls to zero. However, as water becomes scarce in $s2$, long-run prices become relatively inelastic until the value exceeds a user's ability to pay (long-run choke price P_*), or where no further water is available. As noted above, however, in the short-run producers may be willing to pay above the long-run choke price, up to P'_*. While Figure 1 helps understand how producers adapt to a state of nature once it is revealed, it is less useful for teasing apart: (i) the heterogeneity of production systems and producer adaptation responses; (ii) the decision-making process as a state of nature is revealed over time; (iii) the decision-making process in response to changed frequency of the state space; or (iv) a changed state-space description. In such cases, water supplied to each entitlement is unknown at the beginning of a season – an initial announcement defines the base quantity supplied, while subsequent announcements may increase the supply to each entitlement as new state of nature information is revealed (e.g. rainfall events or water policy changes). Once water is allocated in the system, it cannot be reduced in subsequent periods. These factors are considered in more detail below: issues (i) and (ii) are discussed in the following text, while issues (iii) and (iv) are discussed in Section 5.

Figure 2 acknowledges that water supply – used as an agricultural production input over time – can be treated as a stochastic function, where nature provides a defined water supply between 0 and 1.4θ consistent with the properties of SCA technology detailed above. Following earlier studies (e.g. Adamson *et al.* 2009), we assume that the probability π of each state ($s1$, $s2$, $s3$) occurring is (0.5, 0.2, 0.3), respectively. If $s2$ is revealed, a producer faces a water input supply distribution from 0 to θ, with a mean supply of 0.6θ. If $s1$ is revealed, the distribution range shifts from 0.6θ to 1.2θ with a mean supply θ. Finally, if $s3$ is revealed, the distribution range shifts again from θ to 1.4θ, with a mean supply of 1.2θ. This stochastic representation of water inputs (x) provided by s thus defines the rational decision-making bounds.
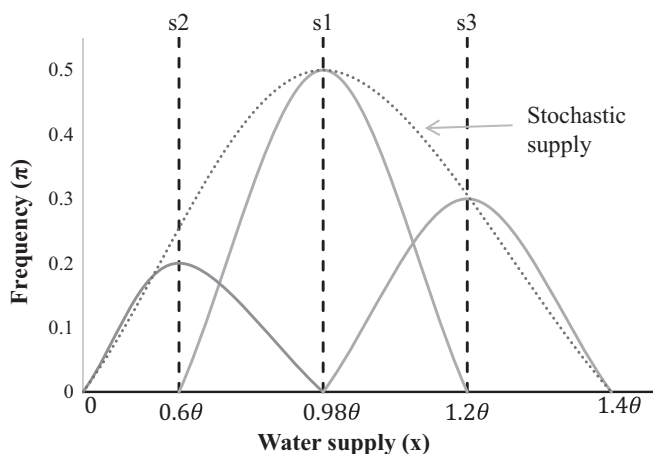
Figure 2 Representation of a stochastic state-contingent water supply.

Water availability decision-making signals are provided when initial supply announcements involve $x < 0.6\theta$ or $x \geq 1.2\theta$; for example, users could alter output decisions or (re)balance water inputs via trade (where institutionally possible and/or supply/demand permits). However, a supply distribution $0.6\theta \geq x \leq \theta$ highlights the critical role initial allocation announcements play in decision making. Opening allocations within this range imply possible future increases, but without guarantee, and thus outcomes will be uncertain until the final state is realised. In response, producers will likely adopt heterogeneous water use/management strategies dependent on: past experience and how well those strategies worked under similar conditions; current investment towards improved water-use efficiency; and any limitations (e.g. trade, regulatory or land constraints). To illustrate this heterogeneity and the importance of allocation announcements, we develop the following simplified choice set model.

For all producer groups, total water supply in a given state (TWs) is the sum of announced supply ($AS_{s,n}$) towards all water entitlements over a given number (n) of allocation announcements:

$$TW_s = \sum_{i=1}^{n} AS_{s,n}$$

where the sum of announced allocation supply is the product of the water entitlement portfolio E – which is a matrix with dimensions $[E \times 1]$ - and the reliability of those entitlements ER with dimensions $[E \times S \times n]$:

$$AS_{s,n} = E \times ER_{s,n}.$$

Crop water requirements by state (WR_s) are the sum of maintenance water (MW_s) required to keep a crop alive (akin to the Figure 1 short-run choke price) and productive water (PW_s) required to generate a commercial yield:

$$WR_s = (MW_s + PW_s).$$

At a minimum, if $TW_s < MWs$ the crop dies. We can now illustrate decision-making differences between perennial and annual crop producers in a two-period game (Figure 3) between the producer and nature (as per Quiggin and Chambers 2004) within the state space. In our game, there are two announcement periods ($n = 2$) and a commodity can survive without water or yield loss until ($n = 2$) is revealed.

4.1 Perennial producers

At ($n = 1$), if $AS_{s,1} < MW_s$, a perennial (e.g. grape) producer has two key options to provide future MW_s requirements depending on their attitude to risk. If the majority of producers believe that the future state will be $s1$, risk-neutral and/or risk-taking producers could do nothing and assume that $AS_{s,2}$ will satisfice MW_s with no impact on the capital root stock; but they will forgo productive yields. As the maintenance supply gap $MG = MW_s - AS_{s,1} \rightarrow AS_{s,1} - MW_s$, the producer becomes the ultimate risk-taker, betting that
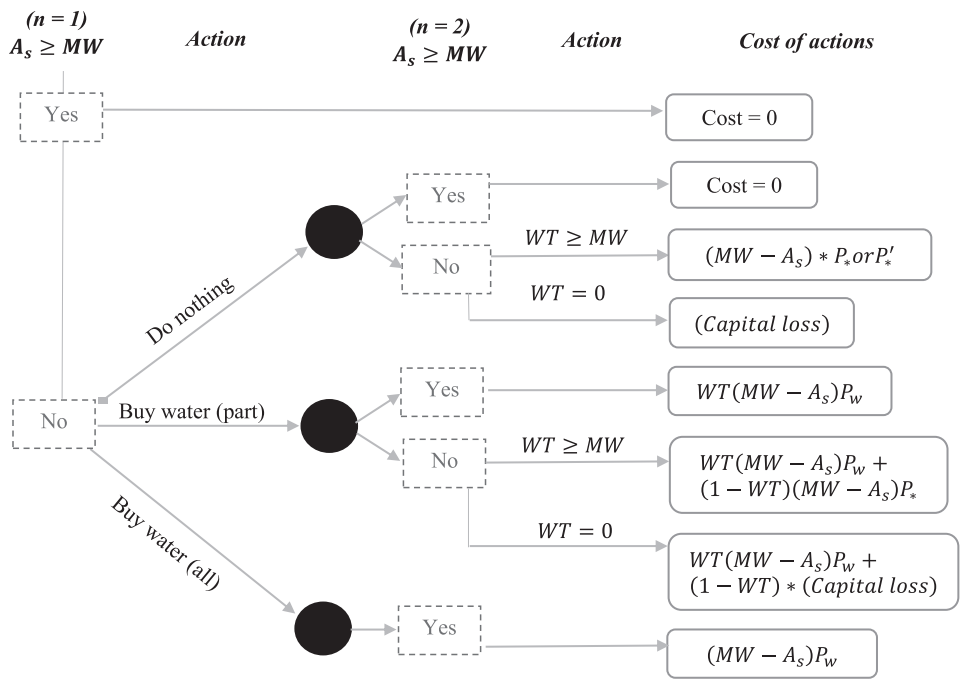

Figure 3 Two-period game for producer decision-making.

$AS_{s,2} = MW_s - AS_{s,1}$. If $AS_{s,2} < MW_s - AS_{s,1}$ and the producer wishes to keep the crop alive, they may be willing to pay the choke price P_* or P'_* per megalitre if water is available and they are not financially constrained. The cost of this strategy will be $MG \times P_*$ or P'_*.[1] However, if water is not available, the producer may be forced to reduce their irrigated area until $TW_{s,n} = WR_s$. Consequently, the producer will lose the relevant capital invested and, assuming they replant in future, the opportunity costs associated with bringing forward investments for each replanted hectare.

Alternatively, the risk-averse producer could enter the water market at ($n = 1$), purchasing water ($WT_{s,1}$) to offset MG. As $WT_{s,1} \rightarrow MG$, the producer is betting that $AS_{s,2} \rightarrow 0$; they can be described as the ultimate risk-averse producer. Further, if at ($n = 1$) the majority of producers believe that the future state will be $s1$, then the price of water at ($n = 1$) will likely be close to p_w. Ultimately, this may prove the better strategy because, once the final state is revealed at ($n = 2$), should $WT_1 + TW_s > WR_s$, the producer can utilise surplus supply to: bring idle land into production if there are no binding constraints and if profitable to do so; generate a water market return; deliver carry-over benefits in the subsequent year if they believe $TW_s < WR_s$; or deliver third-party benefits (e.g. environmental or return flow positive externalities). Instead, if $WT_1 + TW_s < WR_s$, the producer can repeat the strategy adopted at ($n = 1$) and purchase more water ($WT_{s,2}$), or revert to the risk-neutral/taking strategy of maintaining capital stocks with reduced yields.

Additionally, purchases of water in ($n = 1$) reduce the costs of purchases in ($n = 2$) by WT_1; or, if water is not available, it means that an area equal to that maintained/produced by WT_1 does not have to be removed from production. Thus, when allocating land to perennial production, the risk-averse producer should ensure their water entitlement portfolio provides sufficient water to meet maintenance requirements in all states $AS_{s=2,n=2} = MW_{s,n}$, and that the maximum land they can allocate to production is constrained by $TW_{s=2,n=2}$. This conforms with Rasmussen (2003), who argued that risk-averse producers will use more inputs than risk-neutral producers, especially if that input increases output in adverse states of nature.

4.2 Annual producers

Producers of annual crops (e.g. cotton or rice) provide a different perspective that requires some appreciation of state-general and state-allocable inputs. A state-general input increases outputs in all states of nature. State-allocable inputs reflect a producer's requirement to allocate water inputs towards different uses before the final state of nature s is realised. For annual producers, water is a state allocable input for which $MW_S = 0$ and for which decisions in one period do not affect production potential in another period.

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[1] Note MG is at a maximum where $AS_{s,n} = 0$. However. if $AS_{s,n} > 0$ but $<MG$ then the cost is $<MG \times P_*$ or P'_*.

The risk-averse annual producer will only apply water x if there is sufficient TW_s at either ($n = 1$ or 2) to rationalise the use of their other inputs (land, labour, capital), and where the expected profit from consumptive production is greater than the expected returns from selling $AS_{s,1}$ or $AS_{s,2}$ water on the market. The combination of commodity planting-window constraints and PW requirements provide alternative sets of production systems ($n = 1$, $n = 2$) from which the annual producer can choose to maximise their benefits from allocating water between production and water selling.

If the annual producer plants at ($n = 1$), and ultimately at ($n = 2$) $TW_S < MW_S = 0 + PW_S$, they can engage in the same management choice sets as the perennial producer – but they do not face the risk of losing capital invested in the rootstock, nor the opportunity costs associated with bringing forward investments in perennial root stock replacement. The critical difference is that, for the perennial producer, MW is a state-general input ($MW_S > 0$) and all other PW_S is a state-allocable input that will only be consumed/traded where profitable. Conversely, in the absence of a state-general input $MW_S = 0$, an annual producer enjoys greater flexibility in their choice set as they can treat all water as a state-allocable input, consuming/trading it to maximise their utility. Thus, MW can be considered a fixed input which locks the perennial producer into demanding a minimum supply of water in every state, and increases their vulnerability in drought states. A benefit of employing the SCA then is in its ability to represent a producer's awareness of alternative states, and their recognition of a set of management strategies for each s with a unique set of payoffs. If a producer recognises there is a drought, the SCA model recognises that the available water distributes between 0 to θ, and management alternatives are revealed. Further, ($n = 1$) is partially defined; producers know if it has rained, they can determine storage levels, water prices are signalled, and past experience guides them on the π of each state being realised. But how should producers adapt when prior state expectations (i.e. changes to total water supply shared between property right owners) or the frequency/description of the state-space change?

5. Understanding the nature of future drought events

In Adamson *et al.* (2009), a key finding was that increasing drought state frequency reduced capital reallocation more significantly than an equivalent uniform contraction in water supply. Similarly, Adamson and Loch (2014) determined that environmental water recovery via subsidised irrigation technology encouraged farmers to adopt perennial production systems, with rebound effects expanding total perennial system production. Consequently, total water supply required to meet maintenance flows would increase, and both inherent supply variability and future shocks (by revising θ downwards or increasing the frequency of drought states) posed serious concerns for future water user viability. We explore these outcomes further using a

comparison of increasing drought states of nature, and a reduction in the probability of wet states. This is achieved by representing a constant reduction to water supplied in each state of nature (Figure 4) and reducing the probability of each state occurring (Figure 5).

Water supplied on average to a producer in Figure 2 was $\pi_S\theta_S = 0.98\theta$. As detailed in Table 1, where future drought state probabilities increase to 30 per cent with an equivalent decrease in wet state probability to 20 per cent, the producer is now supplied with 0.92θ on average. There are also three alternative state-contingent production technologies T, with different returns under each state. In the 'current' state of nature, net returns (y = revenue – costs) on average from adopting the Option 1 state-contingent production technology is T1 = Y = $\pi_S y_S$ = \$500/ha. In the same current state outcomes, Option 2 provides $T_2 = Y$ = \$400/ha. The difference between T_1 and T_2 is that, while T_1 provides greater y in both s1 and s2, the T_2 production system technology results in reduced losses per hectare (i.e. \$500 versus \$1,000/hectare). Conversely, Option 1 and Option 3 are identical state contingent production technology systems. However, water supplied via T_3 incurs productivity reductions in θ for each s, such that only 0.94 of every hectare is productive; thus, Y = \$470/ha. For simplicity, it is assumed that decreases in θ and hectares are linear, and the numbers used are illustrative only.

As we shift from 'current' to the 'drought 1' nature, we experience a general decrease of 0.06θ, as s2 increases by 10 per cent at the expense of s3. From the representative data used here, a shift in the frequency of droughts (i.e. where the change in water supply is not uniform across all states) encourages producers to transition towards production systems where the economic exposure to droughts is minimised; but drives greater returns from staying
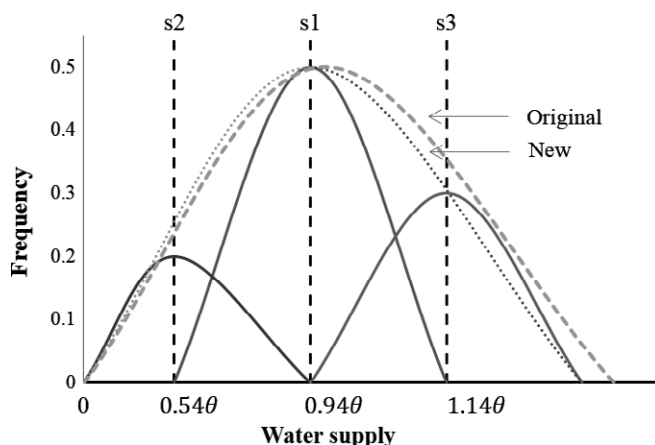

Figure 4 Representation of the stochastic outcomes from changed water supply where future reliability of property rights decrease.
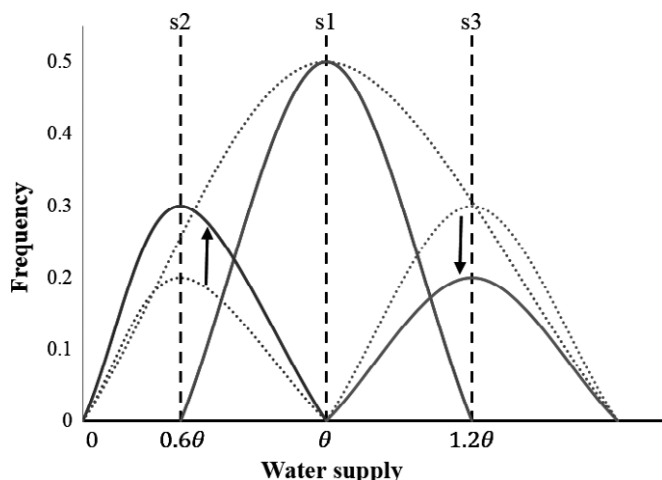
Figure 5 Representation of changed frequency effects on water resources (shift from current to a new drought nature *s2*).

Table 1 Returns from three different state-contingent technology options for alternative nature states in response to a changing climate

State-contingent production system (T_i)	State of nature	Water supply (θ)	Net return ($/ha) ($y$)	π of state occurring for alternative natures		
				Current	Drought 1	Drought 2
Option 1 (T_1)	Normal (*s1*)	0.6θ	500	0.5	0.5	0.5
Current technology	Dry (*s2*)	θ	−1,000	0.2	0.3	0.4
	Wet (*s3*)	1.2θ	1,500	0.3	0.2	0.1
				0.98θ	0.92θ	0.86θ
			Profit (Y)	500	250	0
Option 2 (T_2)	*s1*	0.6θ	400	0.5	0.5	0.5
Drought-tolerant	*s2*	θ	−500	0.2	0.3	0.4
technology	*s3*	1.2θ	1,200	0.3	0.2	0.1
		θ		0.98θ	0.92θ	0.86θ
			Profit (Y)	400	290	120
Option 3 (T_3)	*s1*	0.54θ	=0.94*(500)	0.5	0.5	0.5
Reduced area	*s2*	0.94θ	=0.94*(−1,000)	0.2	0.3	0.4
	s3	1.14θ	=0.94*(1,500)	0.3	0.2	0.1
		θ		0.92θ	0.86θ	0.8θ
			Profit (Y)	470	235	0

passive to risk signals. This is expressed as the difference between the 'current' and 'drought 1' outcomes for T_1 and T_2.

However, as the probability of drought states continues to increase, eventually producers must adopt production systems that: allow gains to be achieved; reduce their relevant production costs to meet revenue levels (e.g. production in that state ceases); or enable the returns in 'normal' and 'good

states' to exceed losses in 'bad' states of nature. For all described solutions, this is the adoption of a new state-contingent production system. For the illustrative data used here, the adoption of T_2 allows a producer to enjoy positive returns in the new 'drought 2' states, rather than simply breaking even if they prefer to remain passive to signals for change, and do not transition away from T_1.

Alternatively, if the reduction in water supply is expressed as a uniform reduction across all states, a producer can adapt by reducing land allocated to productive activity. This is illustrated in Table 1 where T_2 under 'drought 1' is comparable to T_3 in the 'current' climate, where they both experience water supply of 0.92θ. Therefore, modelling the adverse nature of climate change (i.e. less future water supply) as a smooth downward reduction in supply would be far preferable to a system that creates hard supply shocks (i.e. more drought frequency). In revisiting Figures 4 and 5 though, it is important to consider how the states of nature fit with the traditional stochastic water supply curve. Within a modelling process using a Monte Carlo approach to simulate the uncertainty of water supply, it is possible to create solutions where the differences between the SCA approach and stochastic representation of water supply would be inconsequential.

6. Discussion

Drought and its future variability/frequency is a key factor in the Australian water supply story. But like any other natural data, the past is not necessarily a good predictor of the future. The conversion of rainfall to runoff is complicated, and the forecast of future water natures imprecise. However, longer and more severe droughts are a real possibility (Chiew *et al.* 2011). Therefore, producers' expectations of π_s become critical to their allocation of resources.

Incorrect specification of risk essentially shifts producer perceptions of the reliability of their portfolio of water property rights away from q_w in Figure 1. Current Australian government water supply risk mitigation strategies encourage producer perceptions of greater future water supply reliability – even in future drought conditions – and a gradual transition towards more homogenous production systems (Adamson and Loch 2014). The strategy aimed at modernising irrigation technology may be justified by the government on the basis of providing the agricultural sector with structural adjustment benefits in conjunction with the obvious wealth transfers. However, our findings extend comments made by Nauges *et al.* (2011) that not only should risk mitigation policies complement rather than substitute existing private risk-mitigation responses, but those same policies must encourage reallocation of water entitlements towards enhanced flexibility to deal with future unknowns; rather than incentivising existing water rights owners to remain within industries to increase social welfare. Minimising reliance on 'risky' inputs (Rothschild and Stiglitz 1971), where

uncertainty defines the supply of state-general inputs, will preserve capital investments. The goal of efficiency improvement therefore should be assessed over the long-run, and not the short-run. Hence, any idea of comparing (bench marking) annual performances is misleading, as it assumes homogeneity.

Avoiding gradual transitions towards homogenous Australian production systems are also not helped by periodic public calls for reduced production of so-called thirsty annual commodities such as cotton and rice. Instead, annual commodities should be recognised as a very important risk-mitigating strategy to increase the resilience of Australian agricultural production in dry states of nature, where their production can be temporarily ceased and water stocks transferred to higher capital-value perennial uses. Without annuals, individual producer ability to adapt and mitigate risk becomes much more challenging – and expensive – for Australia in the long-run. If Australian producers lock themselves into more homogenous and inflexible production systems, the cost to preserve capital assets under future adverse drought-state impacts such as altered water supply arrangements and/or increased frequencies of occurrence may create: increased future capital vulnerability; future farm debt problems as returns in positive states of nature fail to exceed losses experienced in more frequent drought states; and increased reliance on both water entitlement and allocation transfers in a relatively more constrained market supply context. As we have shown, future changes to the frequency/variability of water supply distributions across drought states of nature would then have very serious consequences for producers constrained in their ability to adapt (e.g. perennial production systems). In the face of this, we would advocate the adoption of mixed-cropping systems by Australian producers as a valid means to reduce risk over the longer term, and a reduction in policy signals that encourage producers to favour the larger adoption of one system (e.g. perennial) over the other (e.g. annuals).

7. Conclusions

Climate change is expected to aggravate future water supply problems for many countries, as water availability contracts and the frequency and magnitude of droughts increase. Australia's agricultural production is especially susceptible to rainfall variability and, while its agricultural producers have extensive experience of dealing with known climatic variability, their capacity to deal similarly with future climatic outcomes is less clear. They will face new adaptation problem/solution choice sets of which they are currently unaware. The state contingent analysis approach outlined herein helps to illustrate how and why producers currently use state-general and state-allocable inputs to adapt and respond to known and possible future climatic alternative natures. A significant advantage in Australia's historic production mix has been the adoption of both annual and perennial production systems, which have allowed a significant degree of

risk-minimisation during droughts. In the absence of land constraints, producers also had a capacity to respond to positive state outcomes and achieve super-normal profits.

In the future, however, the probability of positive state outcomes is uncertain; production systems may need to adapt to minimise losses and/or achieve positive returns under altered water supply conditions that may arise as a consequence of more frequent drought states. As such, Australian producers must assess whether altering current input/output choice sets in response to possible future climate states will enhance their long-run competitive advantage for both expected new normal and extreme water supply outcomes. Further, policy supporting agricultural sector climate change resilience must avoid poorly designed strategies that increase producer's reliance on 'risky' state-general inputs. We argue current policy strategies could drive producers to more homogeneous production systems over time, which ultimately entail risky adaptation options under future water supply availability or increased drought frequency scenarios. Lastly, our analysis has shown the flexibility of applying SCA towards examining uncertainty surrounding future states of nature under climate change. Our findings, while illustrative, can be extended in a number of informative directions. First, the model could allow for the inclusion of environmental flow parameters and outcomes under different states of nature as a means of exploring the full spectrum of Australian water use, with attendant lessons for other contexts. Alternatively, it could be used to examine the rationale behind producer adoption of flat payoff production functions in states of nature without traditional binding constraints. Finally, a better understanding of water property right structures and their outcomes under different states could be analysed within such a model.

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