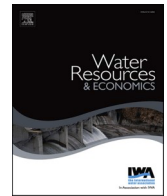




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journal homepage: <http://www.elsevier.com/locate/wre>

(g)etting to the point: The problem with water risk and uncertainty

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ARTICLE INFO

Keywords:

Uncertainty
Unawareness
Water
Transaction costs
Tipping points

ABSTRACT

Where we may be aware that a problem exists, but have only an incomplete description of the drivers and/or possible management solutions, we will be unaware/uncertain about future returns from, and risks to, private and public investments in capital (i.e. social, natural, economic, cultural and political). This paper explores the unawareness/uncertainty problem by coupling Arrow's states of nature approach for dealing with uncertainty with Rothschild and Stiglitz's exploration of inputs and increasing risk. This results in a modified Just-Pope production function equation isolating inputs to i) protect base capital (natural, social or private) and/or ii) generate an output. By exploring water input supply unawareness via alternative states of nature we may identify tipping points where current technology fails, resulting in irreversible losses of private and public capital tied to water inputs. We conclude by discussing the value of quantifying minimum-input requirements and identifying critical tipping-point outcomes in water systems, increased benefits/risks from transformed landscapes chasing higher economic returns, and the need for adaptive public arrangements in response. These insights may help us to understand future risk to natural capital from rising incentives to steal increasingly constrained resources that may trigger revised risk-sharing arrangements, and some limits to analyses relying on perfect foresight requirements by decision-makers.

1. Introduction

Where we may be aware that a problem exists, but have only an incomplete description of the drivers and/or possible management solutions, we will be uncertain about future returns from and risks to private and public investments in capital (i.e. social, natural, economic, cultural and political). Incomplete descriptions of problems or their outcomes limit applications of standard expected utility paradigms [1] where there will be insufficient observations of outcomes to inform beneficial decision-making. As a consequence, investors considering long-lived benefits and costs, irreversibilities and unique one-time investments may favour real-option approaches as a basis for decision-making [2]. However, this is usually only true for a small number of projects (ibid.), and in the majority of cases decision-makers must compare the probability of future failure with the probability of achieving minimum required rewards to assess risk-reduction given the uncertainty of future shocks [3].

An example of this problem is any complex agricultural and environmental choice reliant on (increasingly) uncertain water inputs to exist and function. Water risk and uncertainty could arise through increased unawareness via changes to the frequency of current state (e.g. drought, flood) occurrences [4], the reality that expected future water supply states will evolve [5], and/or a need to explore

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<https://doi.org/10.1016/j.wre.2019.100154>

Received 1 April 2019; Received in revised form 21 October 2019; Accepted 23 October 2019

Available online 26 October 2019

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how current management solutions may fail in response [1]—or tipping-points in existing institutional arrangements. Herein we define risk as known-knowns [6] that can be described with some certainty via a probability distribution; for example, a water entitlement right with expected probability of receiving a full allocation in 90% of years. By contrast, we treat uncertainty as a known-unknown that fundamentally changes (identifies) existing (new) probability distributions that trigger altered management responses; for example, new climatic arrangements that reduce the previous reliability of allocations to 65% of years—but with uncertainty as to if/when this may occur.¹ When such positive/negative water supply is realised, water demand may be dramatically altered and optimal management solutions difficult to identify (e.g. non-convex outcomes) under a motivation by decision-makers to protect capital investments.

The greater the uncertainty (i.e. known-unknowns), the riskier a future water investment becomes and the greater the need to identify risk-sharing or mitigating opportunities. In such representations, decision-maker behaviour will evolve in response to varied states of nature (e.g. drought, flood events) enabling analysts to explore any limits associated with bounded rationality from insufficient observations in support of choices [7]. This may allow analysts to identify how people inform decisions via self-discovery or heuristics [8], and some clarity when compared with standard expected utility function applications where decision-makers may be incapable of accurately distributing probabilities to alternative state occurrences [9]. Such analysis also provides some capacity to explore decision-maker awareness of current/possible future state outcomes, knowledge about relevant rules of the game, and how learning to manage current/possible state outcomes drives eventual decision-making [10]. Possible state outcomes may thus occur in individual or combined forms, as alternative descriptions of previous states, or novel management solutions about which decision-makers were previously unaware [3]. As such, we may be able to explore how decision-makers might adapt to sudden and/or altered states, rather than expected outcomes.

In this paper we focus specifically on how any failure to understand or appreciate the consequences of sudden tipping points (e.g. the over-allocation of scarce and variable resource inputs given unawareness with respect to thresholds) may lead to irreversible capital loss outcomes [11].² Our motivation for this study draws on numerous recent examples of management response failures in the water sector where decision-makers have been ‘surprised’ by changes to both the frequency of states of nature and evolutions in the volume of water supplied (i.e. the description of the state), and have rapidly adapted to avoid irreversible consequences. In Cape Town, South Africa, after three years of drought (2015–2017) domestic water supplies were near fully exhausted. Through severe water restrictions, and a significant rainfall event, a critical ‘day-zero’ outcome of municipal supply being shut off was narrowly avoided. A similar period of drought (2015–2017) resulted in the Alqueva Dam in Portugal, Europe’s largest water storage facility, reaching critically low levels. This threatened water supplies to perennial (e.g. olive and almond) irrigators who had been guaranteed annual water allocations. Some restrictions were possible and applied, but ultimately a significant rainfall event prevented large-scale capital loss. Finally, a six year drought event in California, United States, (2011–2017) reduced surface water availability for irrigation and municipal users forcing greater consumption of groundwater. With groundwater aquifers already heavily depleted, increased usage resulted in land subsidence and an estimated irreversible loss of 2% of the aquifer storage [12]. As the relevant institutions battled to manage the issue, and to come up with solutions for water-users, a break in the drought meant that supply was reinstated and the pressure to reform was reduced.

These cases illustrate a common theme, where current institutions and infrastructure are being tested to meet the existing demands for water under increasing requirements to deal with new and uncertain water supply patterns. Increased water supply uncertainty—and/or inappropriate institutional/management arrangements for dealing with scarcity—may therefore drive systems to rapidly approach or exceed critical tipping points resulting in capital (i.e. social, economic, cultural and natural) losses. Increased experience of such outcomes is forcing radical change in management, adaptation, adoption and/or cropping choice sets to prevent water supplies/systems reaching critical failure, but from a reactive rather than proactive perspective. On reflection, all water managers should be questioning how these tipping points were so rapidly reached, could more have been done to identify these tipping points in advance, and what additional/radical future management change or strategies may now be needed. These answers are not straightforward and involve finer-scale commodity data over a long historical record if dynamic change is to be analysed [13], and representations of real world complexity tied closely to an improved capacity to represent and incorporate unawareness/uncertainty into institutional arrangements and assessments of future risk [1].

However, risk and uncertainty do not typically feature in public policy and/or private assessments of the future, especially in terms of investments; even as many contexts commit globally to programs aimed at increased efficiency in the extraction and consumption of water resources. This may be because the means to represent unawareness/uncertainty in decision-making is difficult, creating challenges for properly discounting future effects on our current enjoyment of resources, and/or deliberate disregard of any ‘uncomfortable’ and/or dynamic information via denial, dismissal, design and displacement [14]. Therefore, in this paper we examine how risk/uncertainty has been considered in past investment and irreversible loss assessments based on representations of water input use as a combination of *additive* risk (where any reliance on additional water inputs increases exposure uniformly, which we term (*g*)) and *multiplicative* risk (where decisions to use additional inputs depends on the decision-makers’ relative risk aversion function, which we term (*h*)), and the limits to those approaches. We then outline a framework based on stochastic states of nature that is being applied to represent state outcomes as either greater/less than some defined threshold, which can accommodate tipping-point concepts. This approach advances our thinking about the role of water as (*g*) and (*h*) inputs to explore investment risk, decision-making, and the need

¹ For simplicity this article ignores unknown-unknowns; that is, events about which we have no information.

² This article follows Arrow & Fisher’s (1974) definition of irreversible loss which may be both immediately permanent and/or subsequent due to a positive rate of time required for regeneration that essentially makes the loss irreversible.

to better identify critical thresholds. We further argue that an appreciation of (g) and (h) water input requirements improves our understanding of proximity to critical tipping points, better informs capital investment risk exposure, and highlights the importance of flexible institutions/policies to manage increasingly uncertain futures.

2. Representing uncertainty in decision-making

When exploring unawareness and uncertainty with respect to water resources it is important to realise that supply uncertainty is inversely correlated with the total demand for production inputs; that is, the less water that is available the greater the total demand for scarce resources. As the future becomes more difficult to predict (e.g. climate change impacts on both the supply and demand for water), a combination of decision-maker unawareness with respect to appropriate responses (i.e. behavioural adaptation to incomplete sets of information) and natural constraints within our existing institutions to deal with future realised (lower) supplies of inputs, may drive us rapidly towards tipping points that result in irreversible loss.

In general terms, a tipping point is one at which a small change or incident becomes important enough to cause larger, more significant (potentially exponential or non-convex) change, requiring critical decision-making in response. Examples in the literature frequently discuss socio-political regimes [15], climate systems [16], disease epidemics [17], safety parameters [18], and leverage points for public intervention [19]. Tipping points can also be thought of as a discontinuity between current and future states, based on the probability of future state distributions [20]. It is the future state distribution notion of tipping points that provides a basis for the thinking in this paper. We can begin our discussion using a [21] production function (Equation (1)) that explores the output (z) of a given system from the use of a single input (x):

$$z = g(x) + h(x)_\epsilon \quad (1)$$

The Just-Pope production function describes both additive risk $g(x)$, where the distribution of outputs is not linked to the use of inputs, and multiplicative risk $h(x)_\epsilon$ where the distribution of outputs is directly linked to the use of inputs. In this case, the error term (ϵ) is often derived from historical data, where established (i.e. known) mean-variance values parameterise a probability distribution function in a Monte-Carlo simulation. Just and Pope [22,23] later challenged the use of mean-variance approaches to stylise risk and/or uncertainty in their reviews of stochastic production functions. Rothschild and Stiglitz [24,25] also noted the limits of relying on mean and variance by exploring outcomes from choosing between variables that have the same expected value, but different distributions. Their critical finding was that decision-makers who fail to understand alternative weights in the distribution of tails may choose riskier, rather than safer, investments. Further, while the notion of representing risk and/or uncertainty as a deviation around a mean number may be appealing for partial equilibrium analysis, Rothenberg and Smith [26] explored how uncertainty alone impacted resource/input allocations within a general equilibrium model. The adoption of the general equilibrium approach allowed for an exploration of feedbacks on the allocation of capital to maximise profits in response to uncertainty represented by a production function with a random parameter. Three of their findings (ibid., p 458) are useful for considering long-term capital investment outcomes: (i) short-run production flexibility provides the greatest protection against uncertainty; (ii) national income tends to fall if the production function has a random variable with diminishing returns, but increases when a 'plausible' production function involves a multiplicative random parameter; and (iii) while uncertainty thus decreases aggregate income, the economy will experience both winners and losers. Put another way, the use (allocation) of water inputs can be risk-increasing, risk-decreasing, and/or shared inequitably based on the nature of the capital investment.

2.1. The state contingent approach to representing uncertainty

Past exploration of risk-increasing and risk-decreasing inputs based on mean-variance and changes to asset net returns can provide misleading outcomes, that may expose public/private investment options to tipping points and irreversible loss outcomes. How then might that assessment change if we accounted for a future state in which necessary water inputs cannot be reliably sourced (i.e. there is no supply)? We suggest that a state-contingent analysis (SCA) framework offers effective approaches for considering such risk/uncertainty (unawareness). The SCA framework broadly allows exploration of how decision-makers' behavioural responses change for realised state outcomes. Further, the SCA framework can enable existing institutional arrangements to be tested for suitability in response to realised or predicted future states; that is, identifying where institutions may fail to provide appropriate adaptations to changes in state descriptions, and/or frequency of occurrence. Insights learned may suggest the need for altered behavioural responses/institutions as a consequence.

Early studies used the term 'states of nature' when discussing investment choices under risk/uncertainty. Original work undertaken by Arrow [27] and Debreu [28] examined how decision-makers respond to realised state outcomes (e.g. drought/flood events). Hirshleifer [29,30] further articulated differences between dominant mean-variance approaches for representing risk and uncertainty and state of nature approaches to inform investment choice theory. According to Hirshleifer [29], state of nature approaches reduced the "vagueness" (pg. 534) associated with other uncertainty methodologies, allowing decision-makers to identify both the natural endowments in a given state and any additional required factors of production to obtain an output in that state. Chambers and Quiggin

[31] extended the state of nature approach by merging it with dual optimisation to illustrate how resources can be used to optimise input use in all states by time, place and type [32].³ This established what is now known as the state-contingent analysis (SCA) approach. In SCA models nature (Ω) defines the complete uncertainty space, and Ω can be divided into a series of states of nature (s) to define real and mutually-exclusive sets (S) which describe that uncertainty ($\Omega = \{1, 2, \dots, s, \dots, S\}$). Importantly, the decision-maker has no ability to influence which s occurs. Further, a decision-makers' subjective belief about the frequency/probability (π) of each s occurring is a vector described by ($\pi = \pi_1, \dots, \pi_s$). However, for each s the decision-maker has a set of management options for alternative production systems (technology). This can be represented (Equation (2)) by a "continuous input correspondence, $X: \mathfrak{N}_+^S \rightarrow \mathfrak{N}_+^N$, which maps state-contingent outputs into input sets that are capable of producing that state-contingent output vector" [33]; pg. 514):

$$X(\mathbf{z}) = \{x \in \mathfrak{N}_+^N : \mathbf{x} \text{ can produce } \mathbf{z}\} \quad (2)$$

For each s , the vector of inputs $\mathbf{x} = (x_1, \dots, x_N)$, their prices $\mathbf{w} = (w_1, \dots, w_N)$, and output prices p are known so that revenue can now be represented as:

$$v_s = z_s p_s \forall s \in \Omega, \quad (3)$$

while costs are also now represented as:

$$c_s = w_s x_s \forall s \in \Omega, \quad (4)$$

and expected net profit across nature Ω is:

$$E[Y] = \sum_{s \in \Omega} \pi (v - c) \forall s \in \Omega. \quad (5)$$

Under the above conditions and with perfect foresight regarding inputs, input prices and output prices—and where the decision-maker's management responses to alternative s doesn't alter—we are able to collapse the total nature set Ω . Then, once s is realised, there is no vagueness about how decision-makers should respond. As such, not only is risk/uncertainty completely described, but decision-makers actively respond to that risk/uncertainty by reallocating inputs to obtain known returns.

This combination of completely describing the risk/uncertainty and its outcomes limits the positive/negative impact of unknown-unknowns. This is because when parameterising risk/uncertainty, unknown-unknowns can only be either greater than, or less than, the chosen parameter. For example, in the case where total supply of water (i.e. quantity of water) is the source of risk/uncertainty, the state outcome can only result in more or less water than was expected. However, the severity of the realised water supply outcome may suggest better future technologies for adoption/adaptation in response. Consequently, sensitivity analysis could play a role in determining the thresholds at which existing technologies and institutional frameworks fail. At those failure (tipping) points, if new technologies emerge over time then a new set of s may be required, expanding the total nature set Ω .

2.2. Rethinking total input uncertainty

We can now return to the Just-Pope production function (Equation (1)) specifying output as a function of inputs to underline the importance of thinking about water inputs differently. Recall that inputs in a Just-Pope production function include additive (g) and multiplicative (h) risk. Chambers and Quiggin [34] respecified the Just-Pope production function into an SCA format as $z_s = g(x) + h(x)_{s,e}$ showing that stochastic information may help to explain adaptive decision-maker responses to revealed states of nature. Following that approach, Mallawaarachchi et al. [35] further modified Chambers and Quiggin's equation into $z_s = \zeta_s + h(x)_{s,e}$, where variability is derived from the natural resource base (land quality/Ricardian rent) ζ_s , together with a multiplicative risk derived from a vector of inputs (including water). This model was used to explain dairy farmer adaptation during drought. Also in the context of drought adaptation, Adamson et al. [36] separated water inputs into two distinct types: i) water used to generate outputs and ii) water used to maintain perennial production systems (i.e. keep them alive)—although they did not specify this mathematically. Herein, we merge the concepts from Mallawaarachchi et al. [35] and Adamson et al. [36] allowing a further modification of the SCA production function to separately account for maintenance and productive water inputs as shown in Equation (6):

$$z_s = \zeta_s + g(x)_{s,g} + h(x)_{s,e} \quad (6)$$

The equation illustrates how z is produced by each s on a given land area, using a combination of additive risk from natural soil fertility (ζ) and two multiplicative risk signals for inputs (x): minimum water inputs required to keep the capital invested in production systems alive (g), and inputs required to generate output categories (h). The addition of an error term (e) for (g) beyond Chambers and Quiggin's original equation is deliberate to account for the decision-makers' unawareness of maintenance inputs required in each state. The error term can also represent any uncertainty over a decision-makers' attitude to risk. For example, a risk averse producer

³ Refers to three input types: (i) *non-state-specific (or state-general)* inputs that must be allocated *ex-ante* to the s being realised, and which influence z in all s ; (ii) *state-specific inputs* that are applied *ex-post* to the realisation of s , and which influence z in only that s ; and (iii) *state allocable (flexible) inputs* (costs) that are applied *ex-ante* to s being realised, but where benefits accrue once s is realised.

may over-estimate (g) water requirements, thus contributing in part to (h) water requirements. Logically the equation could also include additive risk from water for greater explanatory power.

We contend that this relatively simple separation of inputs into (g) capital-preserving water and (h) productive water to generate output categories extends beyond the simple game-theoretic approach used by Adamson et al. [36], providing a powerful illustration of a range of issues relevant to water resource users, managers and policy-makers worldwide. Critically, a better quantification of minimum $g(x)$ input requirements enables more informed decision-making, as well as some improved capacity to compare and contrast available policy options—particularly with regard to future uncertainty/unawareness and resource tipping points. In the next section we expand upon these initial concepts to explore total input availability, how decision-making adjustments may be required when inputs reduce by state, and the importance of tipping points in systems for informing a range of future public/private decision-making.

3. Theoretical relevance of fixed (g) input requirements

We begin with our consideration of total water input availability (supply), which is conditional upon the revealed state of nature s within a stochastic supply distribution. Each state has an independent distribution curve which represents the probability of occurrence as well as the stochastic supply of water likely during such events. Some states (s^2) may have a relatively moderate probability of occurrence, but result in a significant quantity of input resources. Other state outcomes (s^3) have both a lower probability but with a reduced total input availability. Importantly, note the minimum (g) and maximum (g^*) input requirements illustrated by the solid arrowed line at the base of the Figure, and the vertical dashed lines at the extreme tails of the outcome distributions. These indicate the point at which no further inputs can be used by the system to facilitate productive outputs (g^*), or the absolute minimum inputs required to maintain the capital base (g)—hence the distance between a zero input availability and the minimum (g) requirement in Fig. 1.

For example, this could be thought of as the minimum water required to keep a rootstock alive for current and future production. If we treat (g) as the minimum then, as stated earlier, all available (h) inputs by state above that water requirement can be used to facilitate productive outputs. The sum of (g) and (h) inputs will therefore fall along the solid line between the zero-intercept and (g^*). However, it follows that if total supply is reduced, then—as long as (g) water input requirements are met—some reallocation at the margin of available (h) inputs will have to occur (e.g. reductions in input allocation between users as total availability falls from h^b to h^c in Fig. 2). To achieve this, the system must have some capacity for flexibility in its design and arrangements (e.g. market-based mechanisms to reallocate resources between users).

Importantly, in s^3 the system is moving closer to minimum input requirements (g). If total input availability falls beyond that tipping point then irreversible capital (i.e. natural, social, cultural and economic) losses may eventuate. We can think about this another way. If we consider total input demand (D) for (h) inputs by state against total water input supply (x), we can match that to total input availability and movements towards minimum (g) requirement levels as total input availability shrinks (LHS of Fig. 3). This shows the positive/negative (as illustrated by the arrows) tipping points between state outcomes, but that all states of nature are grounded by the minimum (g) input requirement (red-dashed line above the grey-shaded area). We could envisage the grey-shaded area as minimum input requirements in water systems for ecological base flows and/or conveyance water requirements to ensure system operation.

From this we can identify how tipping points or changes to the total (g) input requirement in particular will result in (i) a significant need for trade-offs among existing (new) users, (ii) an increasing requirement for the implementation of adaptive private/public systems to facilitate reallocations (where currently not available), else (iii) irreversible capital losses will result. To illustrate this point, let us shrink our focus to the fixed (g) requirements from total available inputs indicated by the dotted red lines in Fig. 4. If the sum of demand for inputs is less than the total available supply (Fig. 4a), the more flexibility the system enjoys to cope with shock or changed state events. As the system approaches the minimum threshold (tipping point – Fig. 4b), its capacity to cope will be reduced

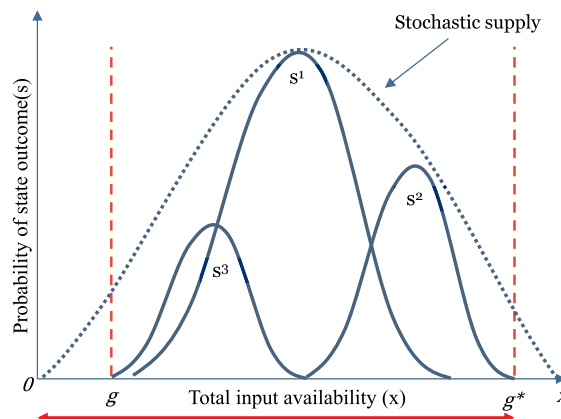


Fig. 1. Total input availability by stochastic state, with min/max (g) requirements.

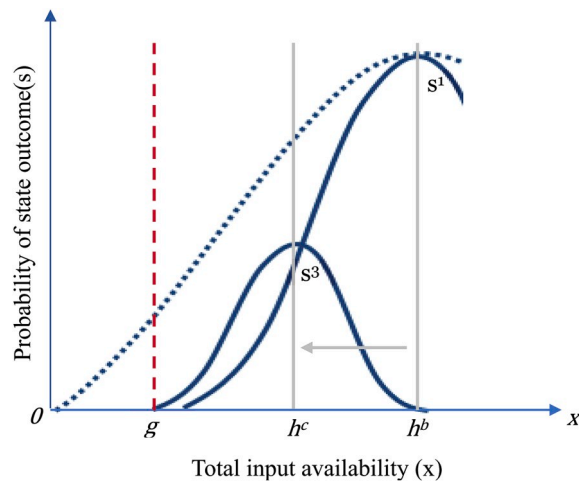


Fig. 2. (g) trade-off requirements under constrained total inputs in new state.

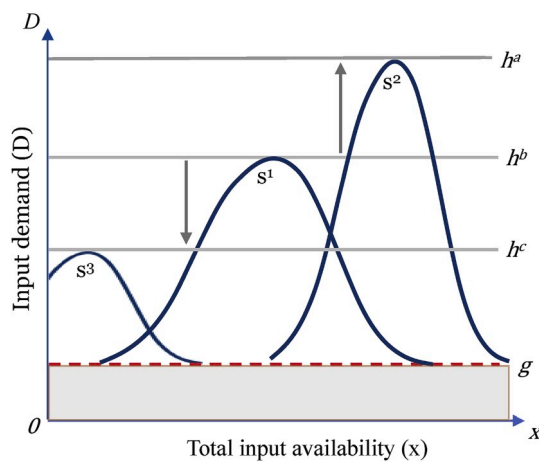


Fig. 3. Total (g) and (h) input supply/demand by state outcome.

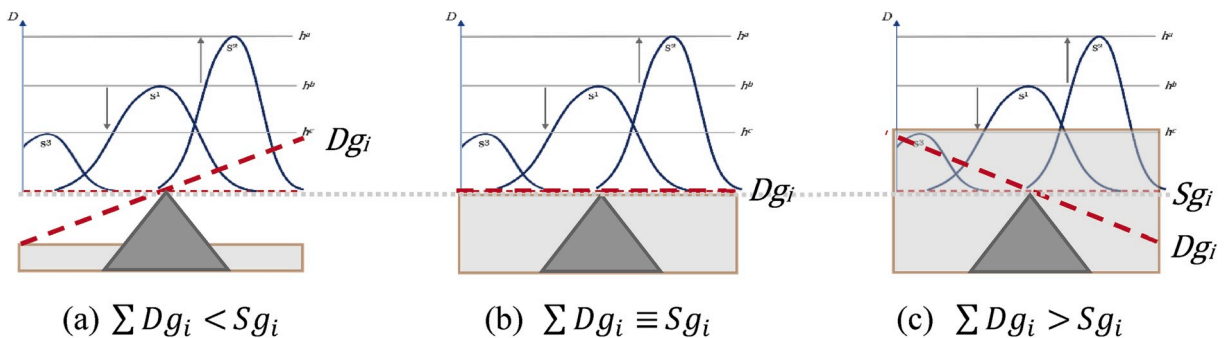


Fig. 4. Positive and negative tipping points for (g) input requirements.

respectively, and the probability of significant change will be increased. If the system breaches the tipping point (Fig. 4c)—recalling that this can result in rapid and exponential change—capital exposure will also grow exponentially, and the system will likely fail. System failures will be especially significant where the minimum water input requirements relate to identified critical functions (e.g. ecological, as shown here in the grey shaded area). Where these requirements are fundamentally breached, all other system functions will likely fail under a cascading impact effect, resulting in multiplicative capital losses—which may also perversely increase during

low supply conditions [37]. A critical point to note is that tipping point breaches of the system in this example impact heaviest during low supply states (Fig. 4c), when systems and users will be most vulnerable to uncertainty and capital losses.

$$(a) \sum Dg_i < Sg_i$$

$$(b) \sum Dg_i \equiv Sg_i$$

$$(c) \sum Dg_i > Sg_i$$

3.1. An empirical example

We have stated that this simple illustrative theory is both powerful and important for the users, managers and policy-makers of resource systems. As an example of the power of these concepts we next examine the transformation that has occurred in the Australian almond industry over the last two decades (Fig. 5). Perennial crops such as almonds require substantial capital investment, and survive for decades. They cannot be fallowed during drought without significant economic losses resulting in demand hardening for critical inputs [38], but they also generate more revenue per unit of water used [39]. Our illustrative Australian example explores how the changing demand for (g) water inputs has rapidly increased as fruit-bearing trees (or those aged six years and older) have reached maturity. It seems likely that during the height of the Millennium Drought (2005–06 to 2008–09) several factors—comparatively high almond commodity prices, severe restrictions on the supply of agricultural water, and government packages to structurally adjust—combined to transform land use from traditional cropping (e.g. 35% reduction in winegrapes between 2005 and 2017 [40]) to new almond plantings with lower water requirements until fully matured (i.e. new perennial plantings).

Between 2005 and 2008, new plantings comprised up to 30% of total area. This resulted in a step-change, and by 2011 production had reached around 58,000 kernel tonnes. By 2020, the almond industry estimates that production will be around 100,000 kernel tonnes, requiring an area of about 48,000 ha of trees [41]. We note that the linear demand trend line superimposed onto Fig. 5 (dotted line) may suggest a change in total water requirements leading toward a potential tipping point, dependent upon where that (g)-input supply point might be.

In fact, the almond industry does have some idea with respect to tipping-point water supply levels. In the United States studies have set a minimum (g) for almonds crops at 50% of total water inputs [13]. For Australia Brown [42] suggests a tipping-point of 3.80 megalitres (ML = one million litres or 0.810 acre-foot) per hectare (Ha), and that most growers prefer to have at least 5.04ML/Ha as a minimum supply to prevent future yield losses. On the basis of industry estimates suggesting mature irrigated crops in Australia consume 14ML/Ha [41], using this figure and the number of hectares planted over time we can see that the industry has a (g) tipping point of approximately 26% of typical water supply, and a preferred minimum supply of at least 36%. This allows us to calculate a

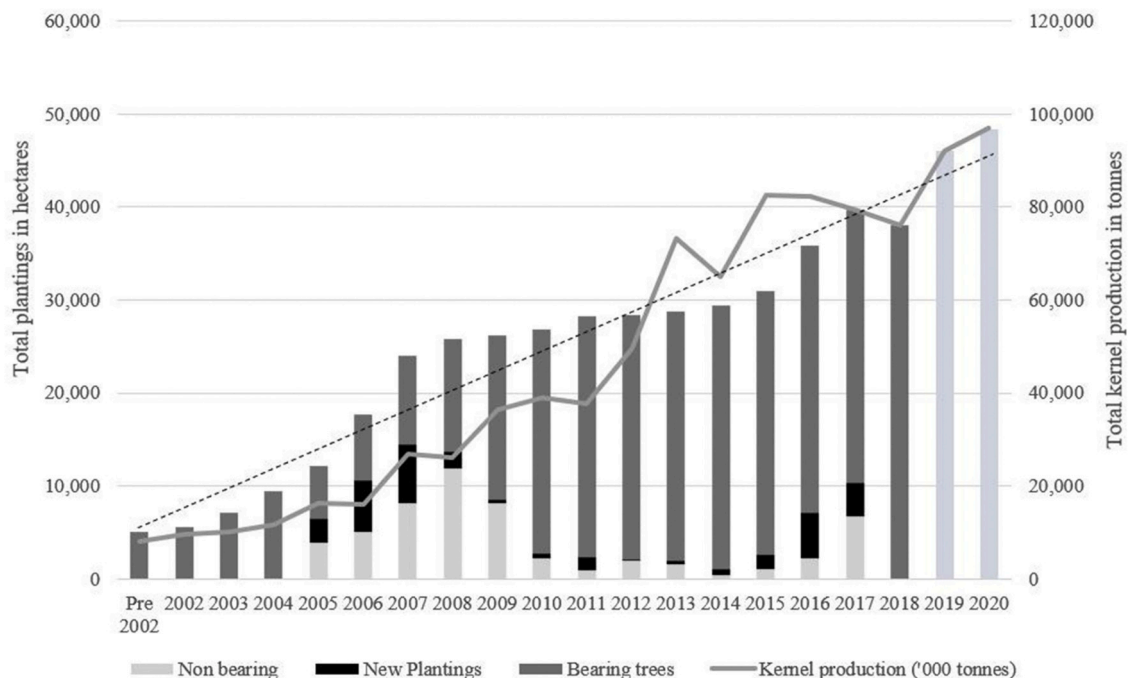


Fig. 5. Growth in almond fruit-bearing trees in Australia, 2002 to 2020 (forecast).

range of g-water requirements across the above industry planting values to identify minimum supply values to maintain industry perennial rootstock (Fig. 6). We can note an initial step-wise shift in the (g)-water requirements following new plantings in 2003, then later step-wise shifts which have increased potential water requirements between 85 GL (GL, or billion megalitres) and 120 GL in 2007, to between 176 GL (26%) and 244 GL (36%) by 2020. The slightly more pronounced exponential increase from 2015 to 2020 based on industry forecasts is particularly worrying in this regard.

However, we do not fully understand: how this changes for almond crop planting density differences; different scales (i.e. basin, catchment or local area); how this may be affected by scope issues such as efficiency changes or sectoral adjustment incentives; how different users may adapt and adjust independently in the face of uncertain outcomes; and/or how climate change may impact upon these issues to shift water supply and demand in the future. This provides us with a great deal of future uncertainty that must be addressed urgently. As the Australian almond industry experiences step changes in water demand to service now largely matured tree-stocks, during periods of low water supply many (new industry) decision-makers will likely be unaware of their total set of adaptation management strategies. In the short-run, this may lead to a willingness to pay prices well above market average to secure water inputs and preserve capital [36]. However, if those markets are unable to fully satisfy water demand, decision-makers faced with extreme downside risk [43] may feel justified in extracting water illegally from other users, including the environment. This may place increased pressure on existing institutions to protect non-economic rights and prevent natural, social and cultural capital losses. Alternatively, in the absence of these two former solutions, farm decision-makers may create a substantial rural debt bomb which may ultimately have to be met by national interventions, as the insurer of last resort. These issues are expanded upon in the next section.

4. Discussion

The theory and basic empirical analysis outlined above suggest a number of issues that could drive a future research agenda. These issues include:

4.1. Increased incorporation of uncertainty into investment assessments

Here we return to our earlier discussion of state contingent analysis (SCA) as a useful tool for incorporating uncertainty/unawareness into models of resource use and decision-making, and for informing future choices. The recent improvements discussed in Section 2.2 above which define uncertainty/unawareness outcomes that are greater or less than a minimum (g) ‘tipping point’ enable analysts to better optimise allocation choices for various constraints or objectives. Alternatively, reversing the process—that is, specifying a management strategy in advance and evaluating it against tipping point outcomes—is also possible. However, both outcomes in this instance are predicated on the availability of good quality data and best-practice water accounting approaches to resource management. Therefore, as our appreciation of the need to incorporate uncertainty/unawareness into public policy grows,

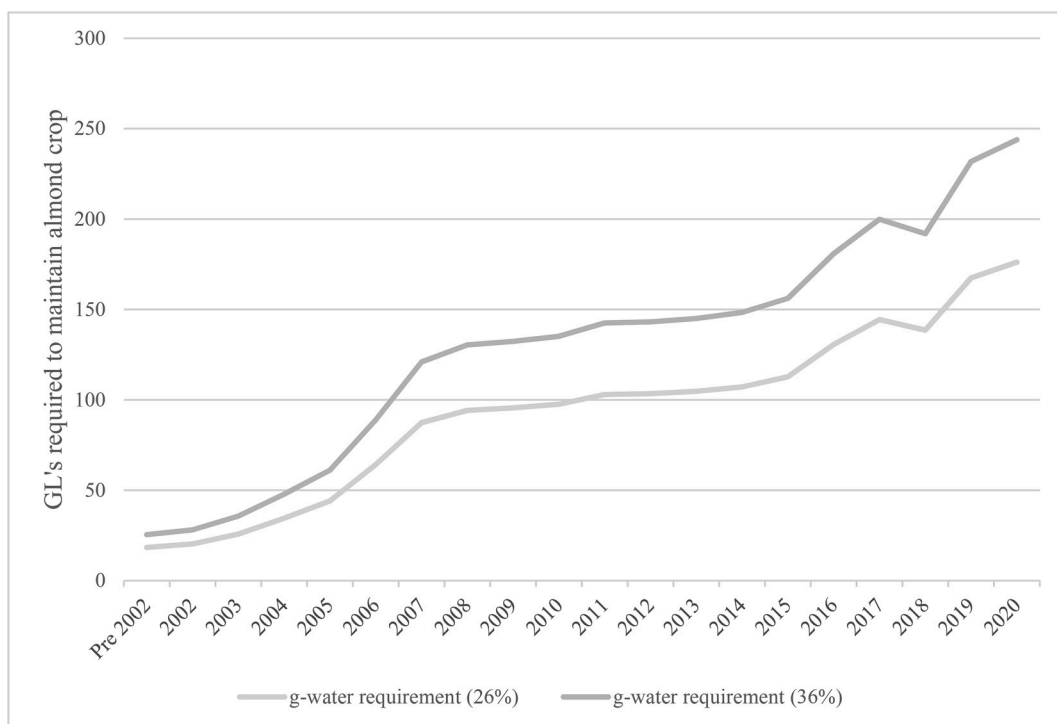


Fig. 6. Minimum almond g-water requirement calculations.

there is an urgent requirement to collect useful data on the minimum (g)-inputs for a range of issues, to implement proper water accounting arrangements, and to explore tipping point outcomes including supply or other shocks (e.g. high prices) using SCA techniques.

For example, a current global focus on water-use efficiency investments both privately and publicly to ‘free-up’ scarce water resources for use elsewhere may be pushing systems towards tipping points where previous supply buffers in the system no longer exist; reducing total system capacity to cope with future supply shortages. Investments in augmented input storage (e.g. dams and weirs in river systems) may also perversely exacerbate these problems by increasing total demand for (g)-inputs under expectations of increased reliability and supply capacity [44]. Hence, in the context of real options theory—which looks at trigger prices under a capacity to suspend production during periods of unfavourable conditions or avoid investment totally [45]—it may instead be useful to couple SCA and benefit-cost analysis (BCA) techniques to explore longer-term investment planning and the impact of shocks on private investment choices. SCA-BCA combined analysis may provide some capacity to examine minimum input levels (i.e. (h) inputs above fixed minimum (g) inputs) needed to achieve $NPV = 0$ (breakeven) outcomes for investment options. This could increase our capacity for evaluating investment choice options to sustain capital or rebound from shock events prior to committing to an investment, and should thus feature in future SCA research.

4.2. Adaptive institutions

An alternative form of investment assessment, especially for public institutions, may involve the use of transaction costs. Put simply, private transaction costs can be thought of as the price of contracting between parties. But at the public policy scale, we can define transaction costs as the expenditure required to design, test and administer a public policy together with the costs of monitoring performance and altering policy arrangements should it become necessary in future. If we are constrained in our capacity to alter future policy, then this is an example of lock-in transition costs. To minimise lock-in costs, and enable institutional arrangements capable of coping with future risk/uncertainty, we must identify and develop adaptive public institutions via comparative analysis. Theory in support of adaptive institutions has recently emerged [46], and some empirical transaction cost analysis (TCA) in support of that theory using ex-post examinations of historic investments and state outcomes has thus far been conducted [47]. More study is needed, but at present the capacity to incorporate future risk/uncertainty is limited.

Thus, similar to the combined research approach discussed above, a coupled SCA-TCA framework (including optimisation and/or BCA) could offer similar public policy investment assessment opportunities. Further, adaptive policy ‘ideas’ could also be parameterised for inclusion as constraints or other objective functions in the model, and then tested against state outcomes as defined in the SCA framework to identify potential policy failure points. This has important implications for public resource managers suggesting that this too should feature in future SCA research.

4.3. Expanded scope as a basis for identifying future risk/uncertainty

For many contexts these issues will seem distant and challenging; suggesting that they can be safely ignored or delayed due to insufficient current evidence or indicators of tipping point thresholds. Yet where insufficient evidence or data in support of robust policy/investment choices exists, appropriate decision-making will suffer under an inability to adequately represent and consider risk or uncertainty. In such contexts, it may be useful to identify more advanced-stage jurisdictions that have dealt with these issues, to determine what lessons could be applied locally. This may highlight: potential transformations toward inflexible future arrangements (e.g. policy lock-in [48]), novel arrangements for dealing with future uncertainty/risk, and/or growing requirements for adaptation—especially where risk assessments do not typically feature in current policy assurance review processes.

An example of this may relate to minimum base flow requirements, as discussed above with respect to conveyance water to deliver minimum (g) water, and which may be several multiples of that minimum volume (Fig. 3). Early attempts to address environmental water input requirements in Australia focused on planned water, where legislation and regulation was altered to accommodate and legally-ensure minimum river flows. While in practice this was somewhat possible in river systems downstream of large dam storage facilities, in other areas the absence of river infrastructure has made maintaining minimum system flows in support of ecological functions more challenging. This has been highlighted in two recent reports investigating large-scale fish deaths along the Darling River system in south-western New South Wales [49,50] where upstream large-scale infrastructure does not exist. Planned water has thus been identified as a useful concept within regulated river systems, but of less value outside those areas.

Further, while market-based reallocations have resulted in the transfer of water to create large quantities of actual environmental rights, alternative measures are still needed to supply base flows in unregulated systems. This continues to be a focus of research and planning work in Australia with important links to the SCA framework. Ultimately, it may be necessary to install prioritised rights to environmental water to ensure that so-called ‘lower’ or temporally newer rights are fully/properly recognised with regard to their higher role in providing a fundamental base for water systems; as well as ensuring that other users do not rely on those rights as a source of risk-minimisation during low supply states of nature. Instead, it may be necessary to implement greater private risk-mitigation responsibilities on consumptive water users as a means of adaptation to future supply uncertainty [45]. This will be especially important where consumptive users continue to ignore system limits, tipping point risks, and/or call for access to supply under ‘fair share’ principles during low supply periods.

4.4. Incentives to act illegally

As we have seen from the earlier illustrative example, there has been some transformation of land use in Australia where winegrapes have reduced their area, and almonds appear to have replaced them. However, while both crops are perennials, they experience different water input needs. Winegrapes average approximately 7 ML/ha, while almonds use 14 ML/ha. Thus, while the transformation of land use may be roughly equivalent, the change in water use is not. Putting aside issues of possible future water delivery constraints under those changes, it is foreseeable that almond producers faced with supply shortages or shocks may have to pay significant future market prices to secure minimum (g)-inputs and avoid irreversible capital loss tipping points—as discussed by Adamson et al. [36]. Alternatively, in the context of poor monitoring and compliance arrangements in many of Australia's river systems [51], producers may opt to extract water illegally. Without adequate legal protection and enforcement, all other right owners may face considerable risk, along with natural capital and national welfare gains. This would result in a system comprising significant winners and losers, consistent with Rothenberg and Smith [26], and increased future uncertainty of sustainable water supply systems into the future. Agricultural water theft is not well-studied in the literature, and as such requires further examination and thought with regard to risk, uncertainty and unawareness drivers. Contingent upon scale and temporal effects, it may be possible to include as a shock parameter in future SCA model analyses.

4.5. A limitation to consider

Finally, a word of caution. While we have espoused the value of the SCA framework for representing and incorporating risk/uncertainty into assessments, it must be noted that the framework presented here assumes a single decision-maker that is possessed of perfect foresight—a heroic assumption. But much the same limitations apply to other models that attempt to shed light on these issues (e.g. positive-mathematical programming [52] or agent-based models [53]). High-quality data, consultation with stakeholders and actual decision-makers, and careful iteration at all development steps of the model may assist to overcome some of these limits. However, the realities comprised of problem scale, capacity to represent the full scope of relevant issues, and temporal changes will always be at odds with modelled outcomes. Just as mean-variance values have been previously viewed as inadequate representations of uncertainty/unawareness, so too the peril of the single number answer when seeking to inform decision-makers. These constraints on our capacity to interact with and inform both private and public decision-makers must also feature in our future SCA model development and output discussions. As an example, future modelling work may explore over-watering decision-responses based on an individual's multiplicative risk attitudes.

5. Conclusion

Future analysis of water resource issues must include strategies for exploring uncertainty. A recent separation of water resource inputs into two major functions that protect capital and generate outputs provides a novel insight into adaptation and the rationale for decision-making that does not conform to expected utility paradigms (non-convex solutions). The capacity of SCA to model these non-convex behavioural responses within each state of nature helps explore what may occur at the farm scale level as individuals reallocate water resources in response to alternative supply states. By examining individual actions, industry wide transformations from market or policy signals, and the capacity of institutions to respond to expected future states of nature researchers may be able to examine a variety of potential tipping points at management/basin-scale levels.

Within a free market-based economy, many contexts will experience a reduced capacity to use command and control methods to constrain production system growth. This will drive an increased requirement to explore and test new policy or program arrangements, and their capacity to cope with risky or uncertain outcomes (i.e. their capacity to reduce or address future unawareness about the risk to capital). For example, as we struggle with tried and recurring policy/political responses to realised droughts and drought relief, this remains an on-going debate. We may be willing to tolerate losses for a period—or even total loss of capital in some cases—although repeated requirements to meet increased private debt in the agricultural sector by public funders may test this resolve; especially where the incidence of acting as an insurer of last resort grows exponentially under risky and uncertain tipping point outcomes. Such repeated bail-out requirements reduce the efficient, sustainable and resilient nature of many local/global objectives. Thus, a greater appreciation of future tipping points may be helpful for avoiding such outcomes, reducing total losses, and identifying the juncture at which risk-sharing/responsibility must finally shift.

In this paper we have explored the development of analytical approaches to risk and uncertainty with respect to water investment and decision-making assessments, and presented a powerful separation of water inputs into their fundamental roles. While this approach may be relevant in other applications (e.g. fishing limits, biosecurity pest impacts, energy limits, environmental watering applications) we contend that there is considerable future scope for further research examining the implications of resource separation in the water context especially. A range of initial research requirements have been proposed, and where the scarcity of total water requirement becomes clearer—and the demand for water grows daily—there is an urgent need to follow these suggestions to inform future decision-making across all levels of water use and management.

Funding and Acknowledgements

Research funding for this work was provided by the Australian Research Council via Grant numbers DE150100328 and DE160100213. We thank two anonymous reviewers for their feedback, and in particular the Editor and one reviewer for their

comments with respect to uncertainty surrounding over-watering actions by risk averse producers. Dr Adamson is also grateful for the opportunity to develop this work as part of a *Giner de los Rios* Scholarship at the University of Alcalá in 2019.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wre.2019.100154>.

References

- [1] S. Polasky, C.L. Kling, S.A. Levin, S.R. Carpenter, G.C. Daily, P.R. Ehrlich, G.M. Heal, J. Lubchenco, Role of economics in analyzing the environment and sustainable development, *Proc. Natl. Acad. Sci.* 116 (2019) 5233–5238.
- [2] K.D. Frederick, Adapting to climate impacts on the supply and demand for water, in: K.D. Frederick, D.C. Major, E.Z. Stakhiv (Eds.), *Climate Change and Water Resources Planning Criteria*, Springer Netherlands, Dordrecht, 1997.
- [3] P. Hildebrandt, T. Knoke, Investment decisions under uncertainty—a methodological review on forest science studies, *For. Policy Econ.* 13 (2011) 1–15.
- [4] R. Chambers, J. Quiggin, *Uncertainty, Production, Choice and Agency: the State Contingent Approach*, Cambridge University Press, Cambridge, 2000.
- [5] D. Adamson, T. Mallawaarachchi, J. Quiggin, Declining inflows and more frequent droughts in the Murray-Darling Basin: climate change, impacts and adaptation, *Aust. J. Agric. Resour. Econ.* 53 (2009) 345–366.
- [6] D.H. Rumsfeld, DoD News Briefing - Secretary Rumsfeld and General Myers, US Department of Defense, Washington DC, 2002.
- [7] H.A. Simon, A behavioral model of rational choice, *Q. J. Econ.* 69 (1955) 99–118.
- [8] S. Grant, J. Quiggin, Bounded awareness, heuristics and the precautionary principle, *J. Econ. Behav. Organ.* (2013) in press.
- [9] J. Hirshleifer, J.G. Riley, The analytics of uncertainty and information—an expository survey, *J. Econ. Lit.* 17 (1979) 1375–1421.
- [10] S. Grant, J. Quiggin, The evolution of awareness, *J. Econ. Psychol.* 63 (2017) 86–92.
- [11] O. Banerjee, R. Bark, J. Connor, N.D. Crossman, An ecosystem services approach to estimating economic losses associated with drought, *Ecol. Econ.* 91 (2013) 19–27.
- [12] C. Ojha, M. Shirzaei, S. Werth, D.F. Argus, T.G. Farr, Sustained groundwater loss in California's Central Valley exacerbated by intense drought periods, *Water Resour. Res.* 54 (2018) 4449–4460.
- [13] N. Mall, J. Herman, Water shortage risks from perennial crop expansion in California's Central Valley, *Environ. Res. Lett.* (2019) (in press).
- [14] S. Rayner, Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses, *Econ. Soc.* 41 (2012) 107–125.
- [15] M. Pelling, K. Dill, Disaster politics: tipping points for change in the adaptation of sociopolitical regimes, *Prog. Hum. Geogr.* 34 (2010) 21–37.
- [16] T.M. Lenton, Early warning of climate tipping points, *Nat. Clim. Chang.* 1 (2011) 201.
- [17] L. Chen, R. Liu, Z.-P. Liu, M. Li, K. Aihara, Detecting early-warning signals for sudden deterioration of complex diseases by dynamical network biomarkers, *Sci. Rep.* 2 (2012) 342.
- [18] L. Kuntz, R. Mennicken, S. Scholtes, Stress on the ward: evidence of safety tipping points in hospitals, *Manag. Sci.* 61 (2014) 754–771.
- [19] T. Mai, S. Mushtaq, A. Loch, K. Reardon-Smith, D.-A. An-Vo, A systems thinking approach to water trade: finding leverage for sustainable development, *Land Use Policy* 82 (2019) 595–608.
- [20] P. Lamberson, S.E. Page, Tipping points, *Q. J. Political Sci.* 7 (2012) 175–208.
- [21] R. Just, R. Pope, On the Relationship of Input Decisions and Risk, Division of Agricultural Sciences, University of California, Davis, CA, 1976.
- [22] R.E. Just, R.D. Pope, Stochastic specification of production functions and economic implications, *J. Econom.* 7 (1978) 67–86.
- [23] R.E. Just, R.D. Pope, Production function estimation and related risk considerations, *Am. J. Agric. Econ.* 61 (1979) 276–284.
- [24] M. Rothschild, J.E. Stiglitz, Increasing risk: I. A definition, *J. Econ. Theory* 2 (1970) 225–243.
- [25] M. Rothschild, J.E. Stiglitz, Increasing risk II: its economic consequences, *J. Econ. Theory* 3 (1971) 66–84.
- [26] T.J. Rothenberg, K.R. Smith, The effect of uncertainty on resource allocation in a general equilibrium model, *Q. J. Econ.* 85 (1971) 440–459.
- [27] K.J. Arrow, Le rôle des valeurs boursières pour la répartition la meilleure des risques, *Econométrie*, 41–47, CNRS, Paris; translated as the role of securities in the optimal allocation of risk bearing, *Rev. Econ. Stud.* 31 (1953) 91–96.
- [28] G. Debreu, *The Theory of Value*, Wiley, New York, 1959.
- [29] J. Hirshleifer, Investment decision under uncertainty: choice—theoretic approaches, *Q. J. Econ.* 79 (1965) 509–536.
- [30] J. Hirshleifer, Investment decision under uncertainty: applications of the state-preference approach, *Q. J. Econ.* 80 (1966) 252–277.
- [31] R.G. Chambers, J. Quiggin, *Uncertainty, Production, Choice, and Agency: the State-Contingent Approach*, Cambridge University Press, New York, 2000.
- [32] S. Rasmussen, Criteria for optimal production under uncertainty. The state-contingent approach, *Aust. J. Agric. Resour. Econ.* 47 (2003) 447–476.
- [33] R.G. Chambers, J. Quiggin, The state-contingent properties of stochastic production functions, *Am. J. Agric. Econ.* 84 (2002) 513–526.
- [34] R.G. Chambers, J. Quiggin, The state-contingent properties of stochastic production functions, *Am. J. Agric. Econ.* 84 (2002) 513–526.
- [35] T. Mallawaarachchi, C. Nauges, O. Sanders, J. Quiggin, State-contingent analysis of farmers' response to weather variability: irrigated dairy farming in the Murray Valley, Australia, *Aust. J. Agric. Resour. Econ.* 61 (2017) 36–55.
- [36] D. Adamson, A. Loch, K. Schwabe, Adaptation responses to increasing drought frequency, *Aust. J. Agric. Resour. Econ.* 61 (2017) 385–403.
- [37] MDBA, *Losses in the River Murray System 2018-19*, Murray-Darling Basin Authority, Canberra, ACT, 2019.
- [38] R. Johnson, B.A. Cody, *California Agricultural Production and Irrigated Water Use*, Congressional Research Service Sacramento, California, USA, 2015.
- [39] J. Medellín-Azuara, D. Macewan, R.E. Howitt, G. Koruakos, E.C. Dogrul, C.F. Brush, T.N. Kadir, T. Harter, F. Melton, J.R. Lund, Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA, *Hydrogeol. J.* 23 (2015) 1205–1216.
- [40] ABS, 7121.0 - Agricultural Commodities, Canberra: Australian Bureau of Statistics, Australia, 2018, pp. 2016–2017.
- [41] Australian Almonds, *Almond Insights 2017-18*, Almond Board of Australia, Berri, South Australia, 2018.
- [42] B. Brown, *Almond irrigation World round-up: Australia, in: Driving Value through Innovation: 37th Annual Almond Industry Conference*. Modesto CA, 2009.
- [43] A. Zuo, C. Nauges, S.A. Wheeler, Farmers' exposure to risk and their temporary water trading, *Eur. Rev. Agric. Econ.* 42 (2014) 1–24.
- [44] G. Di Baldassarre, N. Wanders, A. Aghakouchak, L. Kuil, S. Rangelcroft, T.I.E. Veldkamp, M. Garcia, P.R. van Oel, K. Breinl, A.F. Van Loon, Water shortages worsened by reservoir effects, *Nat. Sustain.* 1 (2018) 617–622.
- [45] T. Mallawaarachchi, A. McClintock, D. Adamson, J. Quiggin, Investment as an adaptation response to water scarcity, in: J. Quiggin, T. Mallawaarachchi, S. Chambers (Eds.), *Water Policy Reform: Lessons in Sustainability from the Murray-Darling Basin*, Edward Elgar Publishing Limited, Cheltenham, UK, 2012.
- [46] D. Garrick, *Water Allocation in Rivers under Pressure*, Edward Elgar Publishing, Cheltenham, 2015.
- [47] A. Loch, D. Gregg, Salinity management in the Murray-Darling Basin: a transaction cost study, *Water Resour. Res.* 54 (2018) 8813–8827.
- [48] G. Marshall, Transaction costs, collective action and adaptation in managing complex social-ecological systems, *Ecol. Econ.* 88 (2013) 185–194.
- [49] Australian Academy of science, *Investigation of the Causes of Mass Fish Kills in the Menindee Region NSW over the Summer of 2018–2019*, Australian Academy of Science, Canberra, 2019.
- [50] R. Vertessy, D. Barma, L. Baumgartner, S. Mitrovic, F. Sheldon, N. Bond, *Independent Assessment of the 2018-19 Fish Deaths in the Lower Darling - Interim Report*, Independent Panel of Experts, Canberra, 2019.

- [51] K. Matthews, Independent Investigation into NSW Water Management and Compliance: Interim Report, NSW Government, Sydney NSW, 2017.
- [52] G. Doole, D.K. Marsh, Methodological limitations in the evaluation of policies to reduce nitrate leaching from New Zealand agriculture, *Aust. J. Agric. Resour. Econ.* 58 (2014) 78–89.
- [53] C.J.E. Castle, A.T. Crooks, Principles and Concepts of Agent-Based Modelling for Developing Geospatial Simulations, Centre for Advanced Spatial Analysis, University College London, London, UK, 2006.