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Incorporating Uncertainty in the Economic Evaluation of Capital Investments for Water Use Efficiency Improvements

AMI

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ABSTRACT *Long run investments in water-use efficiency are risky, particularly where water is required as a secure input. State of nature representations of supply outcomes provide an increased understanding of the vulnerability of capital, and water users, to adverse events. Using Californian data, we couple cost–benefit analysis to a state contingent analysis approach to explore the riskiness of water-use efficiency investment payoffs and cash-flow outcomes when frequencies of states of nature change over the investment course. Critically, this allows us to represent decision-maker adaptation in the face of risk and uncertainty, and the role that subsidy policy plays in those decisions.* (JEL D81, Q25, Q54)

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1. Introduction

Finite and uncertain supply motivates managers and policy-makers to seek efficient and effective water uses. Increasing technical efficiency in the extraction, delivery and consumption of water may increase its' economic, social and/or environmental welfare-enhancing outcomes but, paradoxically, higher water-use efficiency (WUE) can also result in increased total extraction/consumption of water resources (Loch and Adamson 2015). By increasing total water demand, WUE thus creates positive feedback loops placing greater pressure on water supplies. In this article, we seek to examine WUE capital exposure to future water supply uncertainty through the economic lens of decision-makers.

Our study is motivated by expectations that increased total water demand and uncertain future water supply can amplify private capital investment risk exposure that, when scaled, may result in large irreversible losses. Following Grant and Quiggin (2005), risky events are confined to cases where objective probabilities can be assigned to help explore the outcomes from decision-making. Where events and their consequences cannot be characterized by well-defined subjective probabilities, uncertainty tests the decision-maker's capacity to respond and adapt. Uncertainty thus increases capital exposure to finite water supply. Investments under uncertainty therefore pose challenges for decision-makers. Ordinarily we might assess an investment choice over time using cost–benefit analysis (CBA). However, there is considerable debate surrounding how best to incorporate and/or represent risk and uncertainty in a standard CBA. The approach taken in this article is to understand capital risk exposure at multiple scales by combining CBA with a state contingent analysis (SCA), which we believe offers considerable analytical clarity with respect to understanding capital investment decision-making under uncertainty. This approach to understanding capital risk exposure is consistent with guidelines developed by the IPCC (1994) which specify that evaluations of water management projects (e.g. WUE projects) and their impact should examine the inherent uncertainty of future outcomes—including reductions in irreversible or irretrievable commitment of resources—and perform sensitivity analysis of the estimated benefits and costs (Frederick 1997).

Uncertain climate change impacts on water supply are likely to be particularly important for decisions involving long-lived investments, owing to difficulties in identifying benefits and costs, irreversibilities, and real-option choices (ibid.). This applies to places such as California where future access to surface and groundwater supply is being reduced by an uncertain degree (Hanak et al. 2019). The use of state-contingent analysis would enable us to model uncertain state outcomes that, coupled with an improved understanding of decision-makers' adaptation to realized water supply, enhances our appreciation of: i) why WUE investments may fail to attract private capital investments at a significant scale, ii) how subsidies may incentivize greater WUE adoption, but increase investment risk-exposure across multiple scales, iii) the riskiness of large-scale transitions toward high-value perennial crops, and iv) likely future requirements to modify existing risk-sharing arrangements between water managers and users dependent on social or private benefit objectives in the local context.

2. Risk, Uncertainty and Cost–Benefit Analysis

Well-constructed cost–benefit analysis (CBA) can help explore different trade-offs from allocating factors of production (land, labour and capital) between alternative investment options. In this case, the quantification of future cash flows (expenditure and income) over the life of an investment in alternative WUE options related to almond production, and discounting them back to a net present value, allows for comparisons between alternative capital investment choices (including real-options).

Ordinarily, the net present value (NPV) is the sum of the expected net return from the investment ($E[I]$) over the project duration in years ($t = 0 \ldots n$), divided by a discount rate r (Equation [1]). The result provides a key metric for evaluation in the form of $E[I] = (Y -$

K), where Y is the net annual return derived from the investment and K is the capital invested. Further, $Y = (v - c)$ where revenue (v) is a multiplication of the output (z) and price paid per unit of output (p) so that $v = zp$ and costs (c) account for both fixed and variable expenditures.

$$NPV = \sum_{t=0}^{t=n} \frac{E[I]_t}{(1+r)^t} \quad [1]$$

If $NPV = 0$, then the project has broken even. When $NPV > 0$ the project is profitable. Finally, when $NPV < 0$, the project is expected to make a loss. However, consistent with the IPCC guidelines it is logical to assume that both risk and uncertainty occur when estimating the final generated output, prices paid/received, and WUE investment costs. Thus, representing and quantifying the negative and positive impacts derived from risk and/or uncertainty estimates on any single WUE investment is crucial to understanding the opportunity costs of a full set of investment choices.

The risk and uncertainty debate surrounding CBA estimations of investment choices takes three major forms. First, what is the appropriate discount rate to reflect the values associated with uncertainty: a precautionary principal, or the intra- and/or inter-generational benefits from realigning society towards alternative outcomes (Dietz and Stern 2008)? Second, what is the appropriate way to represent risk and uncertainty to quantify the costs and benefits used in the analysis? Third, it has been argued that the very nature of CBA prevents the uncertainty problem from being reflected , as these events either fundamentally change the nature of the scenarios used to describe outcomes, or result in realized outcomes (e.g. output or prices) that have never been previously experienced (Horowitz and Lange 2014). In what follows, we ignore the first debate issue and focus our analysis on a decision-makers' private investment choices over a fixed time-period (i.e. 25 years). Next, we address the second and third debate issues via an initial discussion of the limitation of mean-variance representation of outcomes, and then illustrate the power of combining state-contingent analysis to dealing with uncertainty within a slightly modified CBA framework.

Risk and Uncertainty within a Traditional CBA Framework

Within a CBA framework, risk/uncertainty is typically included via sensitivity analysis to explore mean and variance of a probability distribution of variables which positively/negatively impact costs/benefits (Merrifield 1997). We can illustrate this using a Just–Pope production function (Equation [2]) that explores output from the use of a single input (e.g. water):

$$z = g(x) + h(x)_{\varepsilon} \qquad [2]$$

The Just–Pope production function describes both additive risk $g(x)$ where any reliance on additional inputs increases exposure uniformly, and multiplicative risk $h(x)_{\varepsilon}$ where decisions to use additional inputs to risk-increasing/decreasing effect will be dependent on the decision-makers' relative risk aversion function. In this case, the error term (ε) is frequently based on past data, where the known mean and variance parameterize a probability distribution function in a Monte Carlo simulation. This allows for a series of outcome-runs to determine the likelihood of an investment covering the accumulated debts associated with its selection.

However, Just and Pope (1978, 1979) challenged the use of mean-variance approaches to stylize risk and/or uncertainty in their reviews of stochastic production functions. Prior to this, Rothschild & Stiglitz (1970, 1971) also noted several limitations of relying on mean-variance by illustrating the outcomes (i.e. identification of a riskier variable) from choosing between variables that had the same expected value, but different mean distributions. One critical limitation, commonly known as *Mean Preserving Spread,* identifies the failure to understand how alternative weights in the distribution of tails can result in investors choosing riskier rather than safer investments. While the notion of representing risk and/or uncertainty as a deviation around a mean number is appealing within partial equilibrium analysis, which is common in CBA due to scope constraints, this approach assumes that the decision-maker remains passive to the signals provided by the source of risk and/or uncertainty. In other words, the analysis may depict the investor (e.g. farmer) as one who refuses to adapt in the face of required change, no matter the uncertainty signal. For example, in the case of irrigated cropping such models may represent any refusal to adapt as continuing with the same irrigated crop even when no water inputs are available. Thus, the nature of risk-increasing/decreasing inputs of production are typically concerned with variability and how that alters the net return on asset(s). However, what is less considered is the situation where capital investment occurs with respect to an input which is the source of uncertainty (e.g. water with highly uncertain supply characteristics, which may drive infinite prices, or make the technological selection worthless on average in the short-run). If we are to incorporate an assessment of that type into our CBA investment evaluation to fit the IPCC guidelines, then we must utilize a modelling approach capable of dealing with uncertainty. For that, we turn to state-contingent analysis models.

State-Contingent Models of Uncertainty

With respect to the analysis of information and uncertainty Hirshleifer and Riley (1979) define two branches of study: *market* uncertainty and *technological* (event) uncertainty. In this case we are interested in event uncertainty and how that relates to future water input states and their impact on investment choices. Assessment frameworks capable of dealing with uncertainty and long-term investment decisions (e.g. WUE capital) also broadly fall into two branches: models where the probabilities of future states are unknown by the decision-maker although possible states are recognized, and models where decision-makers are aware of both the states and their relevant occurrence probabilities can be derived from available data (Götze, Northcott, and Schuster 2008). State contingent analysis (SCA) models of uncertainty are capable of following both these broad approaches. This informs our choice to couple SCA models to our CBA capital investment assessment to operationalize IPCC recommendations on risk assessment.

Early studies used the term 'states of nature' when discussing the assessment of investment choices under exogenous risk and uncertainty. The earliest work was undertaken by Arrow (1953) and Debreu (1959), providing a capacity to represent how decision-makers respond to realized alternative states (e.g. drought/flood events). Graham (1981) used this approach to explore farmers' willingness to pay for a public dam project that provided water supply in dry states of nature, and flood mitigation in wet states. However, it was Hirshleifer's (1965, 1966)[i] work that articulated differences between the dominant mean-variance approach and the state of nature representations of risk or uncertainty to inform investment choices. According to Hirshleifer (1965), the state of nature approach removed the *"vagueness"* (pg. 534) associated with other uncertainty methodologies, as it allowed the decision-maker to precisely identify both the natural endowments provided in a given state, and the factors of production required to obtain an output in that state. This finding has been reiterated in more recent studies (e.g. Hildebrandt and Knoke 2011).

R. G. Chambers and Quiggin (2000a) subsequently extended the state of nature approach by merging it with dual optimisation to illustrate how resource allocations represent optimizing input use in all states, by time, place and type[ii] (Rasmussen 2003). Following this work, the state of nature approach became the state-contingent analysis (SCA) approach. In the SCA approach, nature ($\boldsymbol{\Omega}$) defines the state space that can be divided into a series of states of nature (s) to define real and mutually-exclusive sets ($\boldsymbol{S}$) describing uncertainty ($\boldsymbol{\Omega} = \{1, 2, \ldots, s, \ldots, S\}$). Importantly the decision-maker has no ability to influence which s occurs; s is determined exogenously. Further, the decision-maker's subjective belief about the frequency ($\boldsymbol{\pi}$) of each s occurring is a probability vector described by ($\boldsymbol{\pi} = \pi_1, \ldots, \pi_s$). However, for each s the decision-maker does have a set of management options giving rise to alternative production possibilities (technology set). This can be represented (Equation [3]) by a "continuous input correspondence, $\boldsymbol{X}\colon \mathfrak{R}_{+}^{S} \rightarrow \mathfrak{R}_{+}^{N}$, which maps state-contingent inputs into output sets that are capable of producing that state-contingent output vector" (R. G. Chambers and Quiggin 2002b, pg. 514):

$$\boldsymbol{X}(\mathrm{z}) = \{\boldsymbol{x} \in \mathfrak{R}_{+}^{N}\colon \mathrm{x\ can\ produce\ z}\} \qquad [3]$$

Consistent with the CBA assessment objectives stated above, for each s the vector of inputs $\mathbf{x} = (x_1, .., x_N)$, their endogenous prices $\mathbf{w} = (w_1, .., w_N)$, and output prices $\boldsymbol{p} = (p_1, .., p_N)$ are state dependent (R. Chambers and Quiggin 2000b), so that revenue can be represented as:

$$\boldsymbol{v_s} = \boldsymbol{z_s p_s} \qquad \forall_s \in \boldsymbol{\Omega}, \qquad [4]$$

while costs can be represented as:

$$\boldsymbol{c_s} = \boldsymbol{w_s x_s} \qquad \forall_s \in \boldsymbol{\Omega}, \qquad [5]$$

and expected net profit across nature Ω is:

$$E[I] = \sum_{s \in \Omega} \boldsymbol{\pi}\,(\boldsymbol{v} - \mathbf{c}) \qquad \forall_s \in \boldsymbol{\Omega}. \qquad [6]$$

Under the above conditions where inputs, input prices and output prices are fully known, and where the decision-maker's management responses to alternative s does not alter, the total nature set Ω can be collapsed. Therefore, once s is realized, there should be no vagueness in how decision-makers should respond. In such cases, not only is the risk and uncertainty completely described but the decision-maker could then actively respond to that risk and uncertainty by reallocating inputs, where possible, via a wider set of management options.

Critically for our assessment, this combination of completely describing uncertainty and the contingent outcomes limits the positive/negative impact of uncertainty. We can express this another way. When parameterising risk and uncertainty any future water supply outcome can only be either greater than, or less than, the chosen parameter. For example, in the case where uncertainty over the total supply of water (i.e. quantity of water) is the source of risk, the outcome can only result in more or less water than was expected. However, the severity of the realized water supply outcome may encourage the adoption of superior technologies (e.g. WUE capital) as a proactive response. Consequently, sensitivity analysis could play a role in informing the thresholds at which a given technology would fail, and encourage the discovery of newer technology alternatives. At those failure points, if new technologies emerge over time, then a new set of s may be required expanding the original total nature set $\mathbf{\Omega}$ as our understanding of those s changes. Concurrently, the new s set may be represented by a new probability distribution $\boldsymbol{\pi}_s$ to reflect the decision-maker's understanding of their s choices.

Importantly from the previous discussion, Equation [6] slots seamlessly into Equation [1], allowing for the coupled CBA-SCA framework as recommended by J. Hirshleifer (1966) and Graham (1981). In this article we thus posit three hypotheses: *H1* that current constraints on the inclusion of uncertainty in CBA assessments can be addressed by our coupled approach; *H2* that incorporating risk and uncertainty in CBA assessment enables robust modelling of water production inputs and WUE capital impacts and a better understanding of private/public capital investment opportunity costs; and *H3* that assessments of WUE investment using a coupled CBA-SCA approach can achieve a better understanding of water as a production input and capital-vulnerability to shocks, suggesting potential change to future risk-sharing arrangements. Before we test these hypotheses, the next section details the value of water inputs in production systems, and the riskiness of capital investments in water-use efficiency.

3. Water Resources in a Production System

Recall the Just–Pope production function (Equation [2]) which specifies output as a function of inputs (e.g. water). Water inputs in the Just–Pope production function include both additive and multiplicative risk. R. G. Chambers and Quiggin (2002a) respecify the Just–Pope production function into an SCA format $\boldsymbol{z_s} = g(x) + \boldsymbol{h}(\boldsymbol{x})_{s,\varepsilon}$, highlighting how stochastic information can be represented to explain adaptive responses to revealed states of nature and their outcomes. Using SCA, Mallawaarachchi et al. (2017) provide a two-stage technology example for dairy sector adaptation to drought. We rewrite their Equation [6] into a single technology set described as $\boldsymbol{z_s} = \boldsymbol{\zeta_s} + \boldsymbol{h}(\boldsymbol{x})_{s,\varepsilon}$, where all variability derives from the natural resource base (e.g. soil fertility) $\boldsymbol{\zeta_s}$, and the multiplicative risk derived from a vector of inputs (including water) to explain dairy farmer adaptation during drought. Also thinking about drought adaptation, Adamson et al. (2017) explore the behavioural responses of different irrigator types (perennial and annual) to protect capital investments. By developing a two-period SCA game against nature where irrigators bet against receiving their water entitlement (i.e. input uncertainty) the authors explain how and why water prices transition from inelastic, unitary elasticity, through to elastic in response to water supply uncertainty. They achieved this by separating water into two distinct input types: i) water used to generate output z, and ii) water used to maintain perennial production systems (i.e. keep them alive)—although they did not specify this mathematically. However, if we merge the concepts from Mallawaarachchi et al. (2017) and Adamson et al. (2017) we can re-represent the SCA production function as:

$$\boldsymbol{z_s} = \boldsymbol{\zeta_s} + \boldsymbol{g}(\boldsymbol{x})_{s,\varepsilon} + \boldsymbol{h}(\boldsymbol{x})_{s,\varepsilon}. \qquad [7]$$

The equation now represents how z is produced in each s, on a given area of land, using a combination of additive risk from natural soil fertility (ζ) and two multiplicative risk signals for water inputs (x): that is, those inputs required to keep the production system alive (g), and water inputs required to generate outputs (h).[iii] Note, $g = 0$ for all annual crops. The addition of an error term for g beyond Chambers and Quiggin's original equation is deliberate to account for the decision-makers' unawareness of inputs required in each state.

This separation of water into g (maintenance water) and h (productive water) illustrates that an inability to meet $g(x)$ units of water results in irreversible losses of capital directly invested in that production system (e.g. rootstock, trellising, and some irrigation equipment). Separation also illustrates the opportunity (real-option) costs of bringing forward perennial production system replanting investments. Adamson et al. (2017) argued that to avoid irreversible losses perennial producers may be willing to pay a risk premium on the price for water that leads to short run financial losses if, on average (in the long-run), the investment at least breaks-even. However, investors may face the prospect of no future access to water—although annual producers may provide access via markets (where available) as they do not require g water between years. This highlights the differences between annual production systems that require water in the relevant state outcome (risk decreasing—short arrows Figure A1a, Appendix A), and perennial production systems that require water across *all* states of nature (risk increasing—long arrow Figure A1b, Appendix A). For simplicity, g is always required as an input for perennial production systems.

As discussed, a common policy approach to reduce the risk associated with water capital investments is WUE. While debate about the value of WUE continues among scientists, water managers and policy-makers, a less-discussed issue is whether or not WUE actually provides greater capital investment protection in the face of rising future risk and uncertainty. Therefore, before detailing the model and results, we first carefully define the terminology used in our investment assessment in the sub-section below.

Water-Use Efficiency as a Risk-Reducing Strategy

Broadly, WUE focuses on technological innovations that enhance the targeted output in the use of water resources. Engineering innovations may reduce losses in water delivery systems. Agronomic innovations may increase outputs per unit of water applied, say by reducing weed competition. Economic innovations may maximize returns per unit of water applied. Perry

(2007) defines different discipline terminologies as: *field application efficiency* (engineering) which is the ratio of crop irrigation water requirements and water delivered to a field; *irrigation efficiency* (agronomic) which is the ratio between water consumed by crops and water diverted; and *water-use productivity* (economic) which is the true dollar value of output produced—including the opportunity cost—per unit of water applied. Alternatively, we could consider a *water-use index* (WUI), which is the crop output (*z*) per unit of water diverted (Barrett Purcell & Associates 1999).

However, these alternative terminologies can lead to confusion and debate in the economics of water-use deliberations. We suggest, similar to Lankford (2012) that, unlike many treatments in the literature, WUE assessments should focus on understanding how total water delivered to the farm gate is utilized. In this context, system inefficiencies inside the farm gate are within the farmers' ability to manipulate through capital investments or management strategies. Everything beyond the farm gate is outside the farmers' control. Thus, to maximize the net economic returns from innovative WUE investment or strategic decisions we must account for the full cost of all water diverted at the farm gate—where the decision-maker will only invest in those options that deliver financial profitability under full resource cost. We therefore focus on *water-use productivity* (or economic WUE) regardless of investment option as our assessment basis, and specify it as $E[I]/ML$; which is the total expected income $E[I]$ generated from all diverted water at the farm gate ML, or more simply the net profit made from all water use activities. Next, alternative WUE investment options can also be redefined using the common denominator ML:

- *Field application efficiency* redefined as (ML'/ML): or the quantity of water required to provide sufficient input to irrigate a production system (ML') from diverted water ML;

- *Irrigation efficiency* defined as (ML^*/ML): or the water consumed by crops ($ML*$) from diverted water ML; and
- *Water Use Index* (WUI) defined as (z/ML): or the output produced z from diverted water ML,
    - where $ML > ML' > ML^* > WUI$.

This allows us to examine how farmers may: reallocate water resources to maximize profits by understanding the opportunity costs of investments in WUE, determine if water is the binding constraint, and/or identify alternative (better) investment choices.

Consequently, we can simplify WUE investment choice sets into three groups (Figure 1, adapted from Skagerboe 1983). First, **farm design choices** $(m = ML - ML')$: this explores the costs and benefits of alternative infrastructure systems to store/deliver water around the farm (e.g. channels from the farm gate, on-farm dams, and pipelines to/from paddocks). Second, **application technology choices** $(a = ML - ML^*)$; these are the capital/practice options used to irrigate paddocks (e.g. flood, drip, sprinkler irrigation). Third, **SCA production system choices** $[\boldsymbol{g}(\boldsymbol{x})_{s,\varepsilon} + \boldsymbol{h}(\boldsymbol{x})_{s,\varepsilon}]$, which account for capital invested in more g $(crop_g)$ or h $(crop_h)$ water-efficient commodities that may require less maintenance/productive inputs to generate similar outputs. Using this approach, we can now explore the risk to alternative investment and/or management strategy decisions associated with farm design, application technology, and SCA production system choices. Most importantly from a risk and uncertainty perspective, we are better able to represent and explore WUE investment and strategic management decision outcomes allowing for the prospect that water inputs may not be available at all times.

When water inputs are not available we reveal the fragility of our four alternative investment choices. First, there is negligible risk exposure to ML' farm design choices if water is not available. Some ongoing maintenance and refurbishment may be required, but there will be no irreversible capital loss. Conversely, when water is not available the capital risk exposure for ML^{*} application technology and/or $(crop_g)\ or\ (crop_h)$ production system investment choices is context specific. For example, under a drip irrigation system if sufficient g water is not available and the rootstock dies, replanting will also require replacement of the drip system. However, for flood-irrigated h water annual crops the risk exposure to application technology and production system capital choices may be minimal in the absence of water inputs. We account for this differential risk exposure and total water input requirements via Equation [8]:

$$\boldsymbol{z}_{s,a} = \boldsymbol{\zeta}_s + \boldsymbol{g}(\boldsymbol{x}_\varepsilon)_{s,a} + \boldsymbol{h}(\boldsymbol{x}_\varepsilon)_{s,a} + \mathbf{m}(\boldsymbol{x}_\varepsilon)_s \qquad [8]$$

In the new specification, output accounts for $\zeta, m, a, crop_g$ or $crop_h$ that includes not only natural land endowments, but also how application technology choice (a) change both g and h water input requirements dependent of crop choices. The water input losses from producing commodity outputs by application technology and delivery infrastructure (m) are also included. The combination of application technology and management practice choices influence both return flows and non-recoverable losses (Lankford 2012).

Consequently, we can now explore: the returns to capital invested in $m, a, crop_g$ or $crop_h$; the gains from increased WUE from changing the composition of g and/or h water input requirements by commodity, and the possible gains from upgrading farm design. Having now specified all of the precursors to the model, in the next section we describe the potential capital risk exposure from changing states of nature which include outcomes where water is both reduced in supply, and not available at all. We also describe the investment scenarios, the dataset/assumptions used, and then analyse investment choice outcomes using our combined CBA-SCA approach.

4. Scenarios & Data

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The applied example is based on developing an almond production system in California's San Joaquin Valley which is predominantly supplied with groundwater resources. The decision-maker's choice problem is how to allocate a capital budget between five alternative production systems: the base case and four variations corresponding to investing in $m, a, crop_g$ or $crop_h$. Each of these investments has different water-use characteristics. To explore any vulnerability in these investment choices to supply shocks, two alternative climate settings are explored: current and new. Finally, two subsidy settings (no subsidy and 50% public subsidy) are used to better understand the incentives required for private investments in WUE. This provides a total of 18 scenarios, where the base case for current and new climate is not explored using the subsidy setting. All scenarios are listed in Table B1 (Appendix B)—note that the scenarios do not include outcomes from upgrading a mix of investment options, or a portfolio involving all investment options. Current climate water supply uncertainty $\mathbf{\Omega} = \{1, 2, 3\}$ is represented by three s (normal, dry and wet) with a frequency 0.5, 0.2, and 0.3 respectively. Under a new climate regime, these frequencies change to 0.25, 0.75, and 0 respectively based on projections from the IPCC (2018). This new climate setting is harsh, and there is no wet state of nature, but the volume of water available in each s does not alter.

All values are in US$. In Table B1 under the Base case, the cost of m is estimated at $94,000, and in each s typical water losses are estimated at 10%, 15% and 10% of total water applied. For example, using Year 1 data presented in Table B3 (Appendix B), total water losses $= m(g + h + a) = 10\%(12.36 + 0 + 3.09) = 1.55\ ac\ in$. To achieve a 25% water saving in m, an alternative farm design will increase base case m costs by 50%. The water losses by m thus reduce to $10\%(75\%)(12.36 + 0 + 3.09) = 1.16/ac\ in$. Alternatively, a decision-maker could invest in standard field application technology a at a cost of $1,620/acre, or select high-quality technology to achieve 25% water savings at a multiplier of 1.5/acre. Finally, it costs approximately $8,070/acre to establish the almond crop (irrigation, crop variety etc.). However, if the decision-maker was to invest in $crop_g$ or $crop_h$ varieties (respectively) by spending an additional 25% to gain the desired varietal attributes, then the respective $g\ or\ h$ water requirements would fall by 10% per annum.

For all scenarios, it is assumed that the decision-maker owns 105 acres of land, of which 100 acres can be used for production, and the residual area is non-productive accounting for the homestead, sheds, and the water delivery system (m). The state-contingent production costs and outputs, costs of in-field technology choices (a), crop variety establishment costs ($crop_g$ or $crop_h$), and the cost of borrowing capital are derived from Yaghmour et al. (2016). The m costs were obtained from https://www.homeadvisor.com/cost/landscape/drill-a-well/ (data accessed 12 November 2018). Data has deliberately not been adjusted for inflation for two reasons: i) to improve the transparency of how the data has been used and modified, and ii) this study is not designed to provide financial advice, but rather explore water use-efficiency concepts.

However, where Yaghmour et al. (2016) use a 23-year period to estimate the annual repayment of establishment costs, this study uses a 25-year period such that the costs fall from \$581/acre to \$558/acre. The full costs of m are summarized in Table B2 (Appendix B). The cost of borrowing capital is 4.75% and it is assumed that the decision-maker borrows 100% of the capital required, and repays this investment back annually over a period of 25 years. Consequently, the annual repayment cost/acre of establishing an almond crop is then \$735/acre (m + a + crop = \$735 = \$65 + \$112 + \$558). The investment period and repayment plan has been deliberately chosen to be identical to the productive life of an almond production system as it provides the opportunity to explore the residual debt if the crop dies in a given year, given by Equation [9].

$$Residual\ loan = \sum_{t=l}^{t} \frac{(a+crop)_t}{(1+r)^t} \qquad [9]$$

where l is the year of investment failure.

Nature and State-Contingent Production Systems

Like many areas of California, the water supply for this farm is derived from groundwater resources. Poorly metered and relatively low-cost access to groundwater resources makes them particularly vulnerable to over extraction, which have resulted in planned caps on total system extraction and/or systematic access reduction (Leahy 2015) to address overdraft (Howitt et al. 2014). Drought and climate change increase the time required to replenish these resources (Famiglietti 2014), exacerbating overdraft rates. In response, well-depth increases as does pumping costs. Thus, it has been assumed that the true availability of water, and its access costs, will change in response to state of nature (Scanlon et al. 2012). Groundwater resources in the southern San Joaquin Valley are particularly vulnerable both in terms of constrained recharge and subsidence (Faunt et al. 2016). As a consequence of the 2007–2010 drought, approximately 2% of California's aquifer storage has been irreversibly lost (Ojha et al. 2018).

Thus, in our model while on-farm water supply is regulated by the use of a reservoir (Table B2), groundwater cost and availability changes by s. In the normal (N) state, groundwater availability is 74 acre-in at a cost of \$22/acre-in; which generates 3000 lb/acre of almond meat. In the dry (D) state, groundwater restrictions reduce availability to 51 acre-in at a cost of \$26/acre-in; but only 2000 lb/acre of almond meat is produced. In the wet state (W), access to groundwater is unrestricted, allowing producer to pump up to 82 acre-in at a cost of \$21/acre-in, and the almond crop yields 3900 lb/acre[iv]. The full description of how groundwater is used in each s by the vector of required inputs appears in Table B3. All data for the division of water by $m, a, crop_g$ or $crop_h$ are approximate. However, the sum of $a, crop_g$ or $crop_h$ for all years is based on Yaghmour et al.'s (2016) estimation of the total water applied per acre. The data for m appears in Table B1, and as such the total groundwater expenditure differs from that of Yaghmour et al. For clarity, in a normal/wet year the sum of losses by m and a account for 27% of total water use per acre (e.g. in Year 1 for a normal state of nature (3.09+1.55)/17= 27%). In a dry year, losses increase to 30% due to higher evapotranspiration rates, etc.

Table B4 (Appendix B) provides all other variable and fixed costs of the production system. At full maturity, annual variable costs will range between approximately $3,560/acre in a dry state, and rise to $4,110/acre in a wet state. The difference in costs is due to groundwater use and costs, other operational expenses, and harvest costs. Finally, for simplicity the analysis assumes that: dry and wet state almond meat production increases proportionally in years 1–5 based on extrapolations of Yaghmour et al.'s (2016) data for the normal state; full crop maturity and almond production occurs from year six; the decision-maker is operating within a perfectly competitive market free of externalities or subsidies (unless tested); the actions of the decision-maker do not alter prices; and there are no barriers preventing industry growth.

5. Results

Table B5 (Appendix B) provides the CBA outcomes from the Base scenario using an SCA framework to explore the risks from investing in almonds. The total cost of the investment is $18,390/acre, and $735/acre is paid off the debt every year for 25 years. The repayment includes all expenditure towards farm design, application technology, and the crop variety choice.

Once the almond crop is in full production, annual average benefits are estimated at around $2,400/acre. Income benefits range from a $300/acre return in a dry year up to $4,100/acre in a wet year. By the end of the 25-year investment, total income of $43,370/acre is expected; although if only normal years occur total income generated would fall slightly to $39,580/acre. The cash flow (benefits–costs) from the investment are therefore calculated to be $25,000/acre, ranging from net losses of –$19,895/acre up to $61,210/acre profit. At a discount rate of 4.75% the NPV is $9,234/acre, the benefit-cost ratio is $1.87, and IRR is 13%.

The CBA results therefore reflect a typical minimum, maximum, and expected outcome analysis. However, it is the additional model representation of how the decision-maker responds to the revealed states that adds clarity on opportunity costs. If the CBA had focused on an annual (i.e. non-g water) production system the decision-maker could alter crop selections, reduce total area planted, and/or cease planting/irrigation entirely in response to water supply uncertainty. Perennial (i.e. g and h-water) production systems do not enjoy such flexibility in their decision options. For perennial systems, net returns rapidly reduce when the state-contingent event frequency changes. Table B6 (Appendix B) summarizes the scenario results from changed climate outcomes, and differences between unsubsidized and subsidized (i.e. 50% funding assistance toward farm design, establishment and variety selection costs) production systems. In both new climate scenarios, all investment choices fail to generate positive returns.

Recall though that the current climate returns are not per acre-per annum; they are total over the life of the project. Therefore, while positive, they are not significant. This is reflected in Figure 2 by the NPV differential compared to the Base scenario, which is slightly positive for investments in a and $crop_g$ at approximately $100/acre over the 25 years, but negative for all other options. Investments in $crop_g$ or $crop_h$ differ here because, while the variety selection costs are similar, the water savings in dry events for $crop_g$ are higher. This illustrates why decision-makers may be relatively unwilling to invest privately in WUE options, even where the risk posed by uncertain water supply to inflexible production systems is clear. A question therefore becomes whether the motivation to invest privately changes if there is some form of financial support available from external sources (e.g. government or NGO funding providers)? We test a scenario where 50% of the total farm design, establishment and variety selection costs are subsidized, and recalculate the CBA outcomes.

In this case, all NPV differentials compared to the Base are positive across all investment choices, and crop variety options provide the highest saving/benefit returns (Figure 3). This highlights the relevance of subsidy support to private investment choices, reflecting reality in many water contexts.

However, 25 years is a long period, over which we should expect to see some shift in climate conditions. Our new climate scenario tests what effects any water supply shock (e.g. capping, systematic access reduction and/or drought) may have on investment outcomes, with respect to the unsubsidized/subsidized scenarios. The new climate settings shift the probability of drought occurrences to 0.75, which is extreme but comparable with expected outcomes reported by IPCC under business as usual arrangements resulting in 1.5° to 2.0° warming (IPCC 2018). Under these conditions, we assume that the probability of Wet states also falls to zero. For farms that enjoy no subsidy support only investments in $crop_g$ technology will result in slightly positive returns; all other options result in neutral or highly negative NPV returns compared to the Base (Figure 4).

Where 50% investment subsidies are available, the NPV returns compared to the Base becomes positive for all of the investment options, with $crop_g$ or $crop_h$ investments becoming initially sound (Figure 5). However, it is critical to return to Table B6 above, and note that total NPV returns over the life of the project are negative in all new climate scenarios.

An alternative way to illustrate the negative effects of extreme climate change from Table B6 above is to chart the cumulative cash flows in each of the 25 years of the project required to cover outstanding debt on a investments and crop variety choices. This reflects the number of years until a break-even point on the project is reached, repayments are fully covered, and the project begins to make profits. In this analysis, m investments are excluded as the farm design is not adversely affected if the crop is irreversibly lost; although this investment option is retained in the analysis for completeness purposes. Figure 6 shows the cumulative cash flow results for the subsidized scenario across the current and new climate probabilities. In the current climate, subsidized investments in $crop_g$ or $crop_h$ achieve break-even in Year 12—all others require approximately three further years to break-even and cover costs. However, under the new climate scenario the project never achieves a positive return over the project life—even when subsidized.

6. Discussion

There are only a few examples of water infrastructure investment assessments that incorporate uncertainty into CBA in ways that are consistent with the IPCC guidelines. With respect to *H1*, we show that SCA approaches can be used to effectively incorporate uncertainty into CBA assessments to provide valuable insight into long-term water-use efficiency investment impacts. These impacts are elaborated upon via our other hypotheses.

With respect to *H2,* incorporating uncertainty into a CBA assessment with SCA will enable detailed modelling of water inputs to production and a better understanding of the private/public opportunity costs in capital budget investment. Our analysis provides further insight into the private (self) investment viability of WUE technology adoption. Most importantly, increased water productivity from investments may not necessarily lead to higher input reliability or profitability, as water supply constraints are exogenously determined by the states of nature. Typically, investment costs can be high, the savings difficult to measure, economic returns may be low, and future water use and supply risk may remain unchanged (Ward and Pulido-Velazquez 2008). Additionally, by holding any water-savings to create a supply buffer against extreme adverse states of nature, decision-makers may reduce their risk to capital loss—but only at the cost of not freeing up resources for alternative uses. Models that fail to reflect alternative states of nature will allocate such reserve stocks back into production, whereas that does not occur in reality. Further, in practice, decision-makers will perceive little benefit from leaving water recovered through efficiency improvements in reserve (David Adamson and Loch 2014).

Our analysis suggests that water-use efficiency investment is only financially plausible where the associated commodity returns are high and the supply of water is very reliable—two factors unlikely to be regularly present in reality. Where private decision-makers appreciate this fact they may be dissuaded from technological investment, and this is reflected in our results. Thus, public support (e.g. subsidies) may be required to incentivize technology uptake. However, these incentives may distort price signals for private investors, and encourage change at the farm level based on distorted returns to capital investments (as shown in our analysis). As subsidies create inefficient welfare transfers, such policies result in poor outcomes from an economic perspective. However, where subsidized WUE adoption policy is a perceived panacea for scarcity challenges (Gomez et al. 2018), the resultant socialisation of risk needs to be considered. As illustrated in our SCA framework, any business as usual climate change outcomes may expose private investors, publicly-encouraged through subsidy incentives, to increased vulnerability . Associated technological transformations to high-value perennial cropping systems would also make private investors more water-dependent and risk-taking under severe future water supply shocks (Expósito and Berbel 2017). Equally, private investors could be exposed to irreversible capital losses and higher long-term volatility in income. In such events, the public as the insurer of last-resort, could likely be held responsible on the basis of their encouragement to adopt the technological change, and as such could be burdened with liability for compensation (David Adamson and Loch 2018).

Any consideration of public subsidies for WUE investments must therefore assess the investment viability from both the private (e.g. profit, income, and/or productivity) and public investment perspectives (e.g. return flows, food security, poverty reduction, and/or resource reallocation) before committing to any co-investment. For example, if we examine this from the single-user perspective, rather than the wider industry or sectoral view, we may miss important ramifications of industry-wide transformations (or societal expectations) under subsidy arrangements. This changes the risk-profile and lowers the user(s)' switching cost of non-action such that WUE can be perceived as the more 'flexible' option (Jack Hirshleifer and Riley 1979). These incentives also alter perceptions about the reliability of water supply by state of nature and any second-round effects resulting from industry-wide transformations (Rothenberg and Smith 1971), lowering incentives to seek additional information on investment options and impacts. Instead, private decision-makers should investigate risk-sharing and/or mitigation measures capable of offsetting some/all of the potential shock impacts (e.g. land and water planning partnerships with government and/or additional high reliability water rights), and incorporate those into their investment assessment and choices. Public policy/program designers would also be well-advised to consider the scale of needed reforms and the probability of future water supply shocks—or other shocks to productions systems (e.g. access caps, pest/disease, trade embargoes, political wavering etc.)—that could negatively affect investment returns before committing to subsidized WUE investments as a solution to future scarcity dilemmas requiring reductions of total water consumption (Loch, Adamson, and Dumbrell 2020). This advice applies equally to all contexts around the world, regardless of their stage of policy and resource-use reform, institutional development, and/or rights establishment.

Finally, the coupled CBA-SCA approach does appear to enable an improved understanding of water as a production system input, and its vulnerability to future shocks (*H3*). As stated above, in many cases transformations to higher WUE in production systems are often coupled to higher reliance on access to secure water supplies. Yet the main benefit that private decision-makers receive from WUE investments is a net reduction in water use by s. As shown here, long-term investments to achieve water use reductions are risky, particularly where the major constraint to productivity and returns is water and actual water reductions remain uncertain based on poor data availability and limited baseline accounting (Lankford 2012). In this context, it becomes critical to understand the production system ratio of $g(x)$ and $h(x)$ water input requirements to identify and explore the exposure of capital to risk in response to changing frequency of states of nature (Loch, Adamson, and Auricht 2019). Further, policy-makers and water managers should consider changes to the description of those states of nature via sensitivity analysis that explore where current WUE technology/management systems fail to deliver long-term benefits.

Study Limitations

Ultimately this is a farm-based example; we need case studies and data at other scales to build basin-scale, regional or even national analysis results. For example, Adamson (2019) is exploring the requirements and use of g and h water at basin scales for environmental benefits. As our assessments scale, unless the net change in water accounts are fully understood future investments will be exposed to increased risk if the net demand for $g(x)$ units of water increases. In the real world the size of a payoff from a long-run investment is rarely derived from a single risk or uncertainty, but rather a number of alternative futures associated with factors that both increase and decrease the rate of return on a given investment. Consequently, in this case as the time taken to offset the cumulative debt is determined by which state of nature is revealed, and the ordering in which those states of nature occur, the repayment timeframe may be significantly altered. As the time required to reduce the debt increases, the possibility of some other ‘bad’ event (hail, disease management, output price collapse etc.) being realized also increases. More work is needed in the state-space to articulate and understand the risk-increasing and risk-decreasing nature of water inputs to production, which will only come from access to quality data and practical applications that assist us to define not only the number of states, but also their descriptions in a range of contexts.

7. Concluding Comments

Long run investments in water-use efficiency (WUE) are risky, particularly where water is required as a secure input to production systems. State of nature representations of water supply outcomes can assist with our increased understanding of the vulnerability of water users to adverse events. In this example, we couple a cost–benefit analysis framework to a state contingent analysis approach to explore the riskiness of WUE investment payoffs and cash-flow outcomes when frequencies of states of nature change over the course of that investment. Critically, this approach also allows us to represent decision-maker adaptation in the face of risk and uncertainty, and requirements for current discussions related to future risk-sharing arrangements. Importantly, dividing WUE investment options into their key components—at the farm scale in this model—adds clarity to the debate surrounding policy options to address future water scarcity challenges. It also offers a useful tool for those interested in managing climate change impacts on investment more broadly.

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Figure 1

Post Farm Gate Investment/Management Choices

Source: Adapted from Skagerboe 1983.

Figure 2

Change in Water Use and NPV Compared to Base (Current Climate/No Subsidy)

Figure 3

Change in Water Use and NPV Compared to Base (Current Climate/Subsidy)

Figure 4

Change in Water Use and NPV Compared to Base (New Climate/No Subsidy)

Figure 5

Change in Water Use and NPV Compared to Base (New Climate/Subsidy)

Figure 6

Years for Cumulative Cash Flow to Pay Residual Debt (Both Climates/Subsidised)

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[i] Note Hirshleifer (1965) uses the term 'state-preference' rather than Arrow's (1953) states of nature.

[ii] Refers to three input types: i) ***non-state-specific (or state-general)*** inputs that must be allocated *ex-ante* to the s being realized, 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*** that are applied *ex-ante* to s being realized, but where benefits accrue once s is realized.

[iii] Plant physiologists discussing crop water consumption may use the terms basal evapotranspiration (ET), or the ET that happens before any useful yield, and productive ET which is associated with biomass formation.

These two elements are somewhat analogous to our g and h; where our g represents the water needed to maintain a perennial crop for production in following years.

[iv] The data for the normal state of nature is from Yaghmour et al.'s (2016) Tables B1 to B3, while the data for the dry and wet state of nature is defined by Table B5.

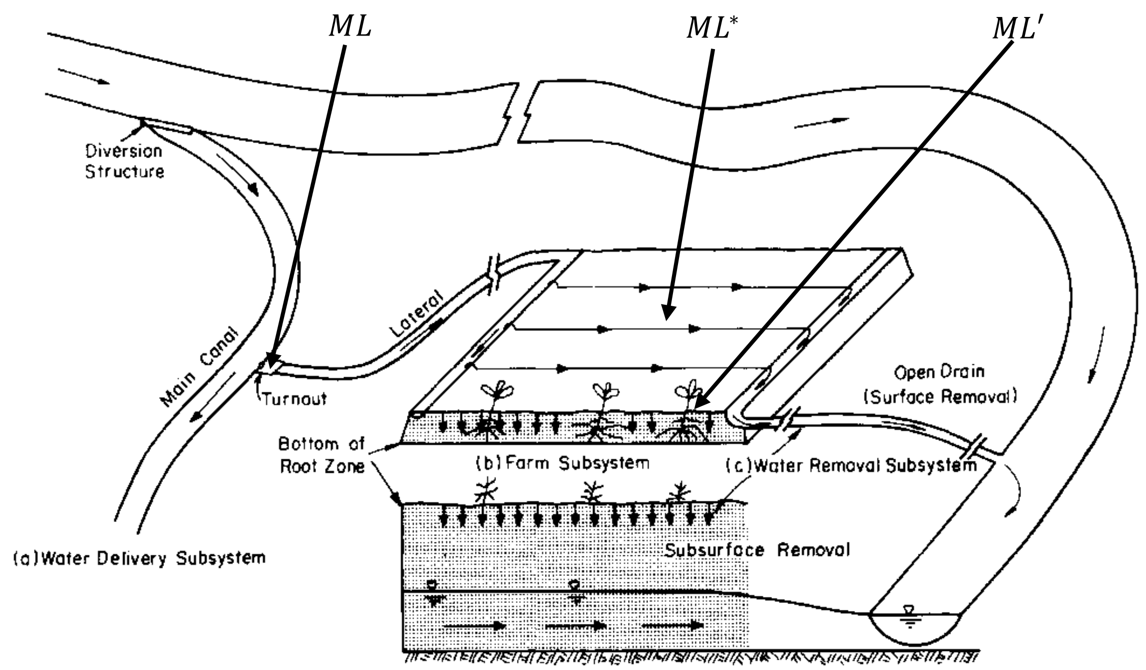

Figure 1: Post farm gate investment/management choices (adapted from Skagerboe 1983)

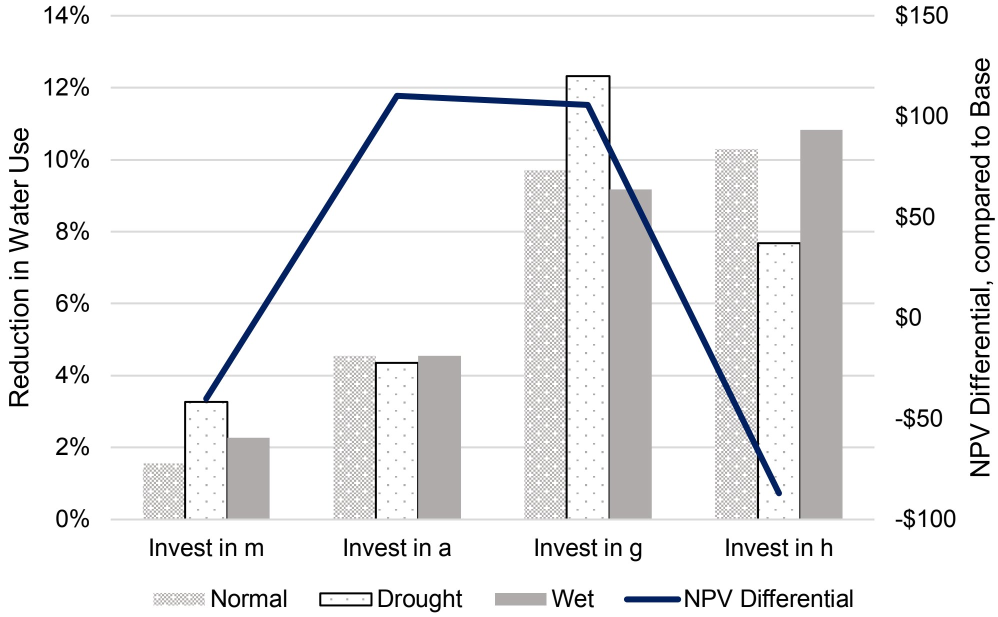

Figure 2: Change in water use and NPV compared to Base (Current Climate/No Subsidy)

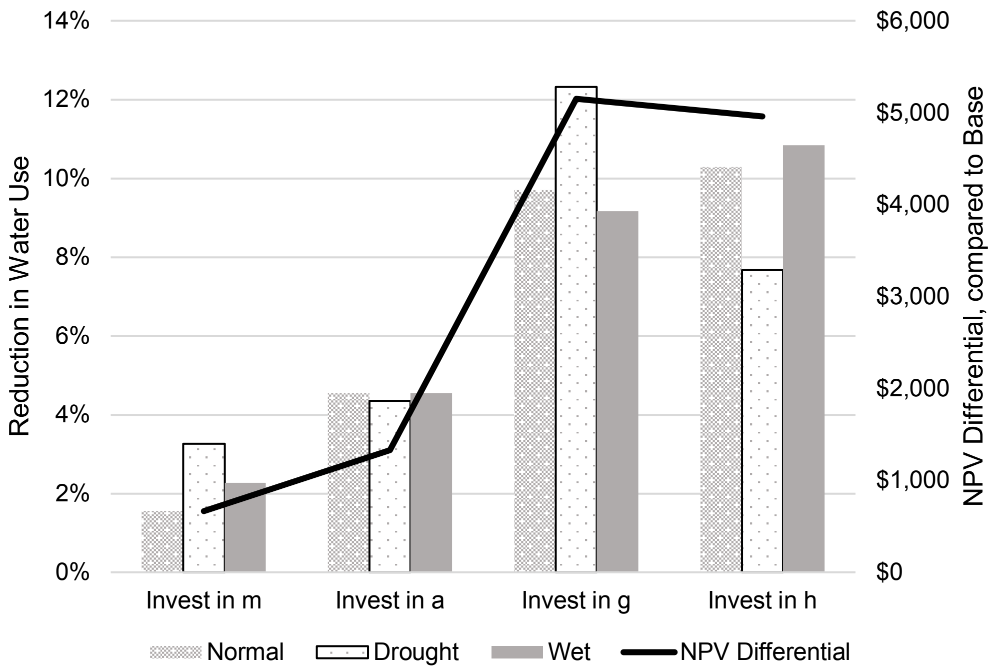

Figure 3: Change in water use and NPV compared to Base (Current Climate/Subsidy)

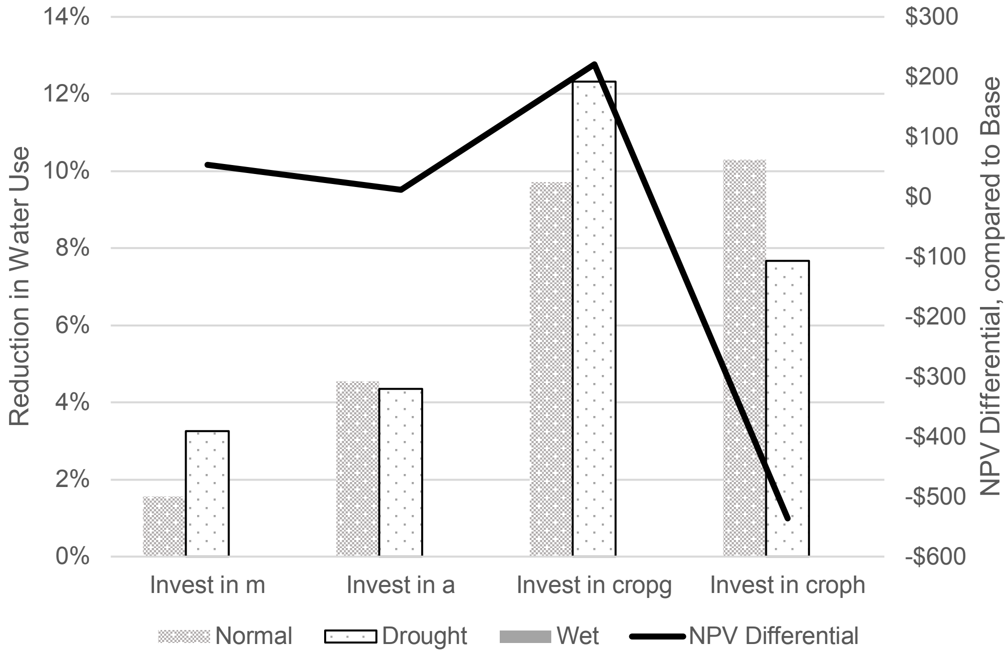

Figure 4: Change in water use and NPV compared to Base (New Climate/No Subsidy)

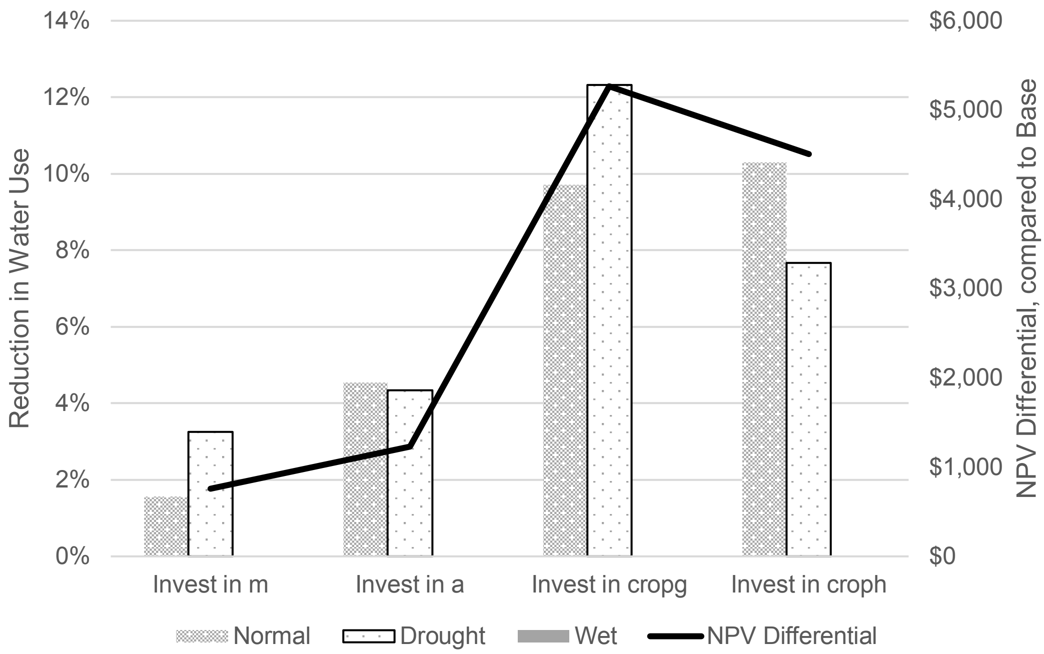

Figure 5: Change in water use and NPV compared to Base (New Climate/Subsidy)

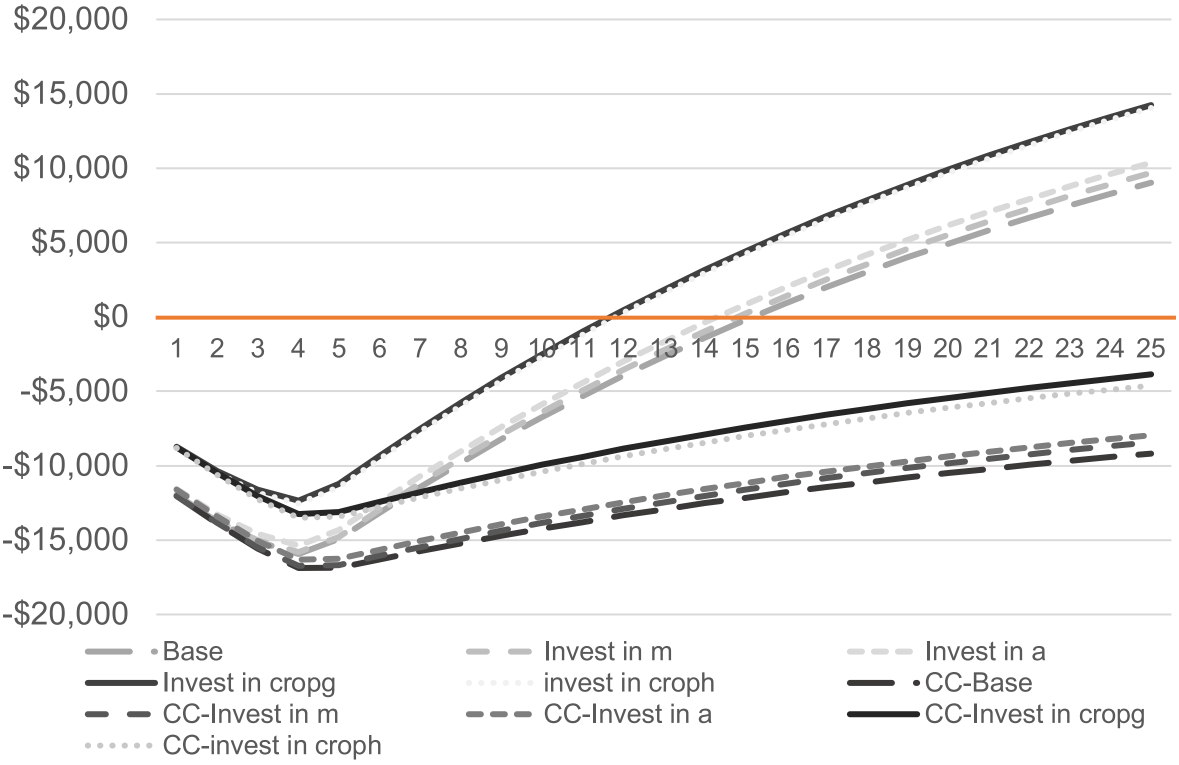

Figure 6: Years for cumulative cash flow to pay residual debt (Both climates/Subsidised)