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Policy interventions to promote the adoption of water saving sprinkler systems: the case of lettuce on the Gnangara Mound

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The potential for improving irrigation scheduling decisions and adoption of more efficient irrigation systems is explored using a bioeconomic simulation model of lettuce production on the Gnangara Mound near Perth, Western Australia. Sandy soils with poor water and nutrient holding capacity are associated with declining marginal productivity of water at high water use, which would create an incentive to reduce water use and to adopt closer sprinkler spacing if farmers had correct information about the declining marginal productivity of water. Incorrect perceptions regarding water–yield relationships lead to over use of water by up to 50 per cent and reduce profits by $475 per crop hectare (12 per cent) in the short run, and remove the incentive to adopt more efficient systems in the long run. Higher water prices create an incentive to reduce irrigation scheduling time in the short term and to adopt more uniform sprinkler systems, and tend to reduce the discrepancies associated with poor information about the marginal productivity of water. The low level of adoption of efficient irrigation systems in the region might be explained partly by historically poor water governance and insufficient extension regarding water productivity and technology.

Key words: bioeconomic models, horticulture, irrigation; technology adoption.

1. Introduction

Policy makers dealing with the problem of over-allocated water resources in irrigated agriculture are often concerned about the socio-political implications of reclaiming irrigation water rights, which relate to the impacts on the local irrigation economy and the community that depends on this economy. The option of reclaiming water through technical efficiency savings, such as piping channels and claiming back the water saved, has been very popular in the Australian context. At the farm scale the main method of reducing the amount of water used whilst maintaining local production is the promotion of water-saving irrigation technologies, which policy makers can target through provision of research and extension services. Evidence from the Murray Darling Basin suggests that broader water policy reform, particularly the clarification of property rights and promotion of water markets, has provided

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strong incentives for adoption of efficient irrigation technologies at the farm level (Marsden Jacob Associates 2000; Young and McColl 2003).

The Gnangara Mound is the main source of water for the irrigation of horticultural crops in the peri-urban area of Perth, Western Australia, where issues of over allocation of consumptive uses, changes in recharge-affecting land uses, and climate change, have all contributed to a rapid decline in groundwater levels in the past decade (Vogwill 2005). Since the Mound also provides 60 per cent of Perth's urban water supply there is a strong policy imperative for improving management, and a major research, planning and consultation exercise is currently underway to identify sustainable land and water management plan for the Mound (Government of Western Australia 2007). Given the rate of decline in the water table in recent years the plan is likely to involve significant reduction in allocations for consumptive uses including horticulture, and the governing agency has already begun investigations of the economic impact of clawing back allocations in different sectors (e.g. Marsden Jacob Associates 2006). At the same time, the Western Australian government has recently joined the National Water Initiative and in the process has undertaken commitments to adopt a more market-orientated approach to water resources management. All of these policy changes will lead to stronger incentives for water conservation in irrigation in the future, which can be contrasted with past policies. Historically, horticulturalists on the Mound have been able to extract water using un-metered bores and with no other form of monitoring of areas grown or quantities consumed against their nominal licenses. A major investment program is currently underway to install meters on farms and this will enable stricter enforcement of licence conditions once they have been determined under the Gnangara Land and Water Management Plan.

The characteristics of irrigated agriculture on the Mound include the use of fixed sprinkler systems, sandy soils with poor water holding capacity, and the prevalence of high wind speeds during crop irrigation. There is evidence to suggest that the majority of irrigators are operating at conditions of very poor irrigation efficiency, largely because sprinkler systems have not been designed to cope with the windy conditions (e.g. Milani 1991; Calder 2005). The main strategy for improving the water use efficiency in sprinkler systems is to improve the sprinkler distribution uniformity, which generally involves capital investment such as placing sprinklers closer together.

A number of previous studies have examined the economics of improving the uniformity of sprinkler irrigation. For example, that higher irrigation depth (or longer scheduling time) is an optimal response to poor uniformity has been demonstrated in a number of contexts (Bernado 1988; Dechmi *et al.* 2003; Brennan and Calder 2006). The trade-off between the economic returns associated with improving uniformity, and the associated investment cost has been explored to some extent (Feinerman *et al.* 1989; Montero Martinez *et al.* 2004). Using a case study of lettuce production in the windy conditions of the Gnangara Mound, Brennan and Calder (2006) found that investment in more uniform sprinkler systems were always justified because of the existence of yield losses from over-watering, based on scientific studies in the region (Phillips *et al.* 2001). However, they also showed that under circumstances where there was a perceived or real yield plateau at high water application, there was little incentive for adoption of more uniform sprinkler systems.

Most previous work on the adoption of irrigation technologies has used positive analysis to analyse the factors affecting adoption, where the hypothesised driver of the adoption, the difference in expected profit or utility earned from a new technology vs. the current one, is not directly observable but the technology choice is. The empirical analysis examines differences between adopters and non-adopters to assess the factors affecting the likelihood of adoption (e.g. Casswell and Zilberman 1985; Green 1996; Moreno and Sunding 2005). Such studies generally focus on choices between major categories of irrigation system, for example between gravity, sprinkler and drip, and the drivers have included environmental conditions, type of crop grown, access to extension services, and personal characteristics of the farmer. The theoretical foundations explaining adoption focus on the learning process, where expectations regarding the performance of a new technology are gradually refined over time, as the potential adopter is exposed to more information on the new technology.

The approach taken in this study is to use normative analysis to investigate the influence of perceptions regarding the performance of a sprinkler technology, on short-term decisions regarding water use, and on longer-term decisions regarding adoption of improved technology. The main focus of the analysis is to identify where policy interventions such as information provision, water pricing and capital investment subsidies might improve the incentive to adopt water saving practices and technologies. The study uses the case of irrigated lettuce production on the Gnangara Mound, where the only change to the farm management practice under consideration is the irrigation scheduling time (the short run decision), and the sprinkler technology (the long run decision). More uniform sprinkler systems are more expensive to install, but improved uniformity of application means that crops can be grown with less water.

The paper is organised into four additional parts. The next section outlines the conceptual model describing the factors affecting water productivity and how information can affect water use scheduling in the short run and irrigation investment decisions in the long run. Section 3 describes the parameterisation of a simulation model which is used in the empirical analysis. Section 4 contains the results, including a discussion of the impact of perceptions regarding water productivity and prices on water use decisions in the short run as well as the perceived benefits of adoption. Conclusions and policy implications are presented in the final section.

2. Conceptual framework

Brennan (2007) presents a conceptual model of irrigation scheduling under conditions of non-uniform spatial application of water, as affected by the design of the irrigation system and the prevailing wind conditions. It is assumed that farmers cannot adjust the watering schedule to avoid adverse wind conditions reflecting the operating constrains on farms in the region (Tim Calder, pers. comm. 2006), thus irrigation scheduling is a decision made under risk. Expected yield is determined by the scheduling time and the realised spatial distribution of precipitation. The framework focuses on the maximisation of expected profit, accounting for non-linearities in the production function but not in the utility function. The key features of the model are summarised below and then some of the reasons why incentives to adopt best practices might be missing are explored.

Consider an irrigation system which delivers a non-uniform pattern of precipitation ω (mm/h) over a field under wind conditions i, defined by the probability density function $\phi_i(\omega)$, and upper and lower limits ω_U and ω_L:

$$\int_{\omega_L}^{\omega_U} \phi_i(\omega_l)d\omega = 1. \tag{1}$$

Let ρ_i be the probability that wind conditions i will be prevailing, and the cumulative density function be defined by $\sum_N \rho_i = 1$. The mean precipitation rate over the entire field can be defined as:

$$\bar{\omega} = \sum_i^N \rho_i \int_{\omega_L}^{\omega_U} \omega_l \phi_i(\omega)d\omega. \tag{2}$$

The quantity of water applied depends not only on the precipitation rate but also on the scheduling decision, or the hours h for which the irrigation system operates. The mean depth of water applied to the field can be denoted as:

$$\bar{W} = h\sum_i^N \rho_i \int_{\omega_L}^{\omega_U} \omega_i \phi_i(\omega)d\omega. \tag{3}$$

Yield $y(W)$ is a function of depth of water applied z and therefore varies over space. The mean yield produced from the field can be defined as:

$$\bar{y}(h) = \sum_i^N \rho_i \int_{\omega_L}^{\omega_U} y_i(h\omega_i)\phi_i(\omega)d\omega. \tag{4}$$

For a given sprinkler design j, defining the shape of $\phi_i(\omega)$, and an annualised capital cost of K, the expected profit earned can be described (in per hectare terms) as:

$$E(\pi_j) = P\sum_i^N \rho_i \int_{\omega_L}^{\omega_U} y_{ij}(h_j\omega_{ij})\phi_{ij}(\omega)d\omega - c_q\bar{y}_j(h_j) - c_w\bar{\omega}_j h_j - K_j \tag{5}$$

where P is the product price, c_q is the non-water variable cost of production associated with producing y, c_w is the marginal cost of water, both assumed to be constants in the analysis.

For a given sprinkler system which has an associated spatial precipitation, the decision maker's problem is to determine the scheduling time h, and the optimal solution is:

$$(P - c_q)\frac{\partial \bar{y}}{\partial h} = c_w \bar{\omega}. \tag{6}$$

Equation (6) states that the contribution to the gross margin, associated with increasing scheduling time, is equal to the marginal cost of an extra hour's watering time. The term $\partial\bar{y}/\partial h$ is the differential of Equation (4) with respect to scheduling hours and can be expressed as:

$$\sum_{i}^{N} \rho_i \int_{\omega_L}^{\omega_U} \frac{\partial y}{\partial W} \omega_j \phi_i(\omega_j) d\omega_j \tag{7}$$

which is the marginal productivity of water depth W multiplied by the precipitation. It depends on the shape of the yield function $y(W)$, and the probability distribution of $\phi_I(\omega)$ at each wind speed i, and the probability of those wind conditions occurring.

The decision to adopt a new technology (denoted by subscript N), given that the farmer has technology j, will be determined by comparisons of expected profit. Since the desirability of adoption of a new technology will depend on useful life of existing technology, two bounds define the economic gain from adoption. In the most pessimistic case, the existing sunk capital is new and in the most optimistic case, the existing capital is at the end of its economic life and needs replacement. The upper bound on the financial gain from adoption can be written:

$$V_j^U = \pi_N - \pi_j = (P - c_q)(\bar{y}_N(h_N) - \bar{y}_j(h_j)) - c_w(\bar{\omega}_N h_N - \bar{\omega}_j h_j) - K_N + K_j \tag{8}$$

where K_N and K_j are the capital investment cost of the new and the current system, on a per crop hectare basis.

The lower bound (sunk capital case) on the benefit of adoption is defined as:

$$V_j^L = V_j^U - K_j. \tag{9}$$

Having defined the short- and long-run conditions for optimising expected profits, potential deviations from the optimal can be explored. The emphasis in the following sections is on information regarding water productivity, sprinkler performance and the opportunity cost of water. Other factors that may explain irrigation scheduling and adoption of more efficient technology are revisited in the discussion.

2.1 Deviation from optimal water use due to poor information about water productivity

Equation (6) describes the first order condition for optimising scheduling time over the short run for a given sprinkler system. This condition is shown in Equation (10) where the symbol ^ is used to denote perceived values that may deviate from true values

$$(P - c_q)\sum_i^N \rho_i \int_{\omega_L}^{\omega_U} \frac{\partial \hat{y}}{\partial W} \hat{\omega}_j \phi_i(\hat{\omega}_j) d\omega_j = c_w \hat{\bar{\omega}} \qquad (10)$$

where $\partial \hat{y}/\partial W$ (the perceived marginal productivity of water), $\hat{\omega}_j$ (the perceived mean precipitation rate) and $\hat{\phi}(\hat{\omega}_j)$ (the perceived spatial distribution of precipitation) may deviate from true values

$$\sum_i^N \rho_i \int_{\omega_L}^{\omega_U} \frac{\partial y}{\partial W} \omega_j \phi_i(\omega_j) d\omega_j .$$

Inaccurate information about the marginal productivity of water will lead profit maximising decision makers to deviate from the potential maximum profit level. For example, the farmer may have inaccurate information about the water–yield relationship. A recent study from the area indicated that there were significant yield losses at high water application rates associated with nitrogen leaching (Phillips *et al.* 2001). If farmers are unaware of this potential for yield loss then they are likely to over-water, as they will perceive a higher productivity to water near the (true) optimal level of application. Similarly, if they do not have correct information about the distribution uniformity of their sprinkler system, they may under- or over-water because their perception regarding productivity of water will deviate from the true value. In these cases a policy to improve information regarding the productivity of water (the water–yield relationship or the distribution uniformity), will result in better water use decisions by profit-maximising farmers.

2.2 Deviation from optimal water use due to poor information about the true price of water

In the present policy setting in the study area, the only cost incurred on water use is the cost of electricity for pumping. However, there are two reasons why the social cost of water may be higher than the private cost of pumping. First, that governance of water resources on the Gnangara Mound has been poor is well recognised, evidenced not only by a lack of metering of most consumptive uses including irrigated agriculture, and continued increases in licensed consumptive uses despite declining groundwater levels; but also by formal, damning, assessment by the Environmental Protection Authority regarding the state of groundwater dependent ecosystems (Environmental Protection Authority 2006).

Whilst allocation issues on the Mound are yet to be resolved, it is likely that in the absence of political interference the quantity allocated to agriculture will be reduced because it is a relatively low-value use compared to urban water supply. This implies that there is an over allocation of water to agriculture at present, and that the scarcity value associated with current water use decisions in agriculture are not accounted for in irrigation decision making.

The second problem is one of nutrient pollution associated with intensive horticulture. Phillips *et al.* (2001) recorded nitrogen leaching in experimental studies on the Gnangara Mound and found, for example, that around 20 per cent of nitrogen was leached when water was applied at the Department of Agriculture recommended rate of 150 per cent of pan evaporation for lettuce. Nutrient concentration in the wetlands downstream of the horticulture area is impacting upon biodiversity (Department of Environment 2004) which may have a social cost. Because of the costs of monitoring of non-point source pollution, market failures are generally corrected using indirect incentives such as taxes or subsidies, or mandatory standards, on factors of production (Shortle and Dunn 1986). In the case of the nutrient leaching problem in this case study, indirect incentives could include fertiliser taxes, or subsidies and taxes on more/less efficient irrigation technology, but one means of simulating the internalisation of the externality problem is to raise the price of water.

Policy initiatives currently in process, including revision of (and likely reductions in) allocations, monitoring of compliance to allocation limits, greater market orientation of water allocation decisions, and placing conditions on licences to reduce external impacts of water use decisions, are likely to result in an increased price or opportunity cost of irrigation water use in the future. The effect of policy reforms that better represent the social opportunity cost of water use can be examined by introducing a variable λ in addition to the private cost of pumping, the new first order conditions are:

$$(P - c_q)\int_{\omega_L}^{\omega_U} \frac{\partial \hat{y}}{\partial W}\hat{\omega}_j \phi(\hat{\omega}_j)d\omega_j = (c_w + \lambda)\hat{\bar{\omega}}. \tag{11}$$

Since the production function is concave, the increase in the right hand side of Equation (11) as a result of the water market will lead to a reduction in water use. The extent to which the water market influences water use will depend on the perceived marginal productivity of water, and the perceived spatial distribution uniformity.

2.3 Information and the incentive to adopt efficient technology

Inaccurate information regarding the marginal productivity of water or its social cost will affect short-run decisions regarding water use, and will subsequently affect both perceived and real benefits from adoption of more efficient technologies. Equations (8) and (9) can be rewritten as (12) and (13) to reflect the importance of perceptions and information.

Perceived benefit of adoption, upper bound (replacement case):

$$V_j^U = (P - c_q)(\hat{y}_N(\hat{h}_N) - \hat{y}_j(\hat{h}_j)) - (c_w + \hat{\lambda})(\hat{\bar{\omega}}_N\hat{h}_N - \hat{\bar{\omega}}_j\hat{h}_j) - K_N + K_j. \quad (12)$$

Perceived benefit of adoption, lower bound (sunk capital case):

$$V_j^L = V_j^U - K_j. \quad (13)$$

These equations demonstrate that the incentive to adopt depends on how the difference is gross margin (the first term in Equation (12)) is impacted by uniformity, and whether this is greater than the additional capital cost of investment. In the case where gross margin differences are small, then capital subsidies on the more efficient investment N might be required to encourage adoption.

The potential information deficiencies in Equations (12) and (13) are the production possibilities from the two technologies ($\hat{y}_N - \hat{y}_j$), the decision regarding h_N and h_j influenced by information regarding the productivity of water and the spatial distribution of precipitation, and information on the unit cost of water application including its scarcity value. In this analysis it is assumed that cost information regarding private costs of production and market prices, including the capital cost of investment, is readily available.

3. Parameterisation of the model

The importance of information regarding these parameters is explored using a case study for lettuce referred to in Brennan and Calder (2006), and comparing the water use and perceived economic returns from three different sprinkler systems of varying spatial uniformity. This set of three designs was drawn from a larger set examined by Lantzke (2003), and is characterised by a particular brand (Toro™) operating at a pressure of 300 kPa. The only difference between the systems is the spacing of the sprinklers which has an impact on distribution uniformity, especially at high wind speeds. The performance of these sprinkler systems at different wind speeds is shown in Table 1. These values can be compared with the internationally accepted standard of 75 per cent. Only the closest spacing (10 m × 10 m) performs consistently at all wind speeds. The other two only meet the acceptable standard under calm conditions, and in the case of the 14 m × 14 m spacing, there is a substantial deviation from the acceptable standard at higher wind speeds. Also shown is the cost of investment and the per-crop-hectare difference in capital cost between the most expensive highest performing system and the others.

3.1 Representing the spatial distribution of precipitation

The spatial distribution of irrigation precipitation was represented using a discrete probability distribution, based on a log normal distribution where

Table 1 Key characteristics of the three sprinkler systems

Spacing (m × m)	Distribution uniformity % at wind speed†			Investment cost‡ ($/ha)	Capital cost ($/crop ha)
	≤ 4 km/h	> 4 and < 17 km/h	≥ 17 km/h		
10 × 10	90	90	90	8166	250
12 × 12	87	72	70	6557	197
14 × 14	75	50	48	5414	159

Source: †Derived from results reported in Lantzke (2003), and ‡from authors' calculations.

the mean was calibrated to fit a typical mean precipitation rate and the variance was determined to give the desired distribution uniformity shown in Table 1, which are a measure of ratio of precipitation at the 25th percentile of the distribution divided by the mean precipitation. Discussions with irrigation experts indicate that a commercial operator would not have the flexibility to adjust time of day watering to avoid high wind speeds, and would not adjust watering regimes in response to wind on a particular day. Hence the differences in performance associated with different wind speeds introduces an element of risk into the model. The irrigator must decide on a scheduling time for a crop given that three alternative wind speeds could occur over the duration of the crop.

To represent misperceptions regarding the spatial distribution of water, we assume that the farmer perceives performance of the sprinkler system to remain at the 'calm condition' performance at all times. This assumption reflects comments made by irrigation industry experts that sprinkler systems 'do not appear to have been designed for windy conditions' (Tim Calder, Department of Agriculture and Food, personal communication, March 2006).

3.2 Representing the productivity of water

Three alternative functional forms were used to represent perceptions regarding the productivity of water. The 'true' functional form was based on experimental results conducted in the region, reported in Phillips *et al.* (2001), which indicated a declining yield at high water application rates. Two typical functional forms were used to represent alternative perceptions; these were the Mitscherlich and Leontief forms. Under the Mitscherlich form there is a strong penalty from under-watering and no penalty from over-watering as the yield plateaus at high water application rates. The Leontief (fixed proportions) assumption was derived by taking agronomic advice regarding crop water requirements from an irrigation scheduling model (Department of Agriculture and Food 2006), and inflating the scheduling time to account for less-than-perfect uniformity by dividing it by the distribution uniformity, a common approach recommended by irrigation experts (e.g. Lantkze 2003). The shape of alternative functional forms used in the analysis is shown in Figure 1.

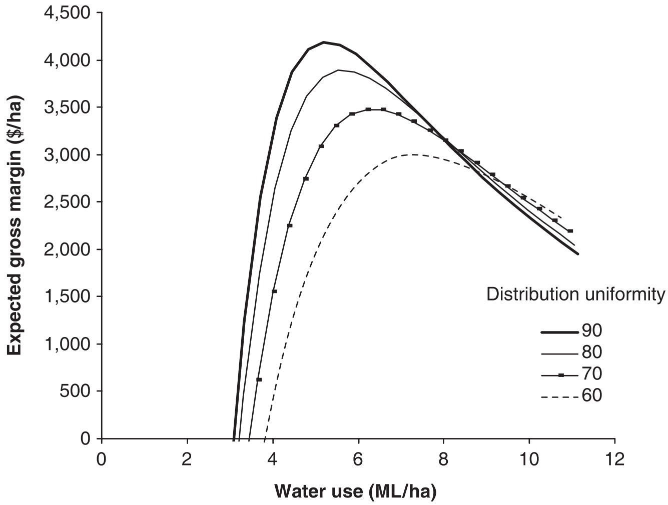

Figure 1 Illustration of the water–yield relationships used in study.

Table 2 Definition of water–yield relationships used in study

	Function	Parameters				
		a	*b*	*c*	*d*	*g*
'Declining yield' (True value†)	$y = a + \dfrac{b + cE}{1 + dE + gE^2}$	31.74	–23.69	0.294	-1.743×10^{-2}	1.43×10^{-4}
'Plateauing yield' (Mitscherlich†)	$y = a(1 - e^{-b(E-c)})$	44.1	55	0.06	—	—
Leontief‡	$y = a$ if $\bar{W} = b$ $y = 0$ if $\bar{W} \neq b$	44.1	Varies	—	—	—

Source: †Calculated from experimental data reported in Phillips *et al.* (2001), ‡*b* is the estimated crop water requirement for a particular season, divided by the distribution uniformity. *Y* is yield in tonnes per hectare and *E* is water applied divided by pan evaporation ×100.

These alternative functional forms are demonstrated in Table 2, where water application is expressed as a percentage of pan evaporation. These values were converted to water quantities in each season using historical data on rainfall and pan evaporation. Economic data was obtained from gross margin and survey data reported by Gartrell (1998, 2001).

4. Results

4.1 The effect of distribution uniformity on the true returns to irrigation

The impact of distribution uniformity on the shape of the gross margin function for the declining yield function is illustrated in Figure 2. The shape of

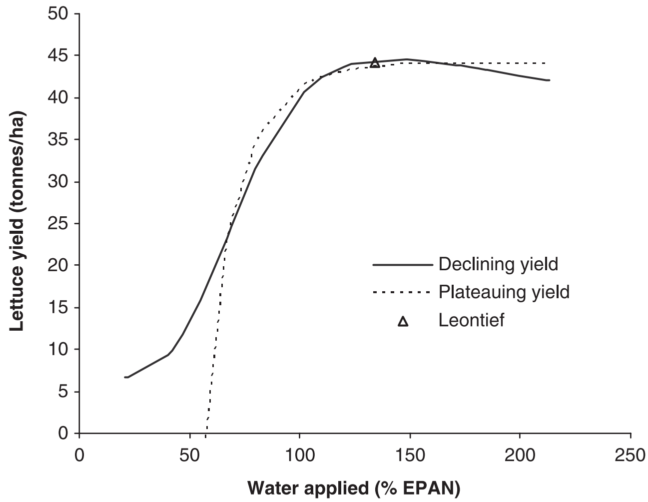

Figure 2 Optimal water use as affected by distribution uniformity.

the curves reflect the underlying yield function, where increasing water use first increases yield and gross margin, but eventually reduces gross margin because of declining and negative productivity. Increasing costs of water application also contribute to a declining gross margin but the cost per ML is only around $50/ML, so the baseline contribution of water cost to the shape of the curve (which falls by 2000 as water is increased between 4 and 10 ML, whereas the water cost is around 300) is limited. The peak of the curve represents the level of water use at which gross margin is maximised. As the distribution uniformity is reduced, the gross margin curve becomes flatter, and the peak moves to the right. This is due to the averaging of effects in different parts of the field: drier patches continue to respond to increasing water application rates whilst the wetter patches begin to suffer declining yields.

4.2 Impact of perceptions regarding yield–water relationship on water use

The impact of perceptions regarding the water–yield relationship on (perceived) optimal water use is shown in Table 3. The first row shows the perfect information case, and illustrates the impact of sprinkler spacing on water use. The optimal water application rate increases by 23 per cent when the spacing is increased to 12 m × 12 m, and is 93 per cent higher than the 10 m × 10 m when the spacing is 14 m × 14 m.

The effect of alternative expectations regarding water–yield functional form is shown in the subsequent two rows. The yield plateauing function results in the highest level of water use at all sprinkler spacings, with 25 per cent higher use even for the most efficient sprinkler design. This is because with this functional form the optimal response is to focus on avoiding under-watering since there is no perceived penalty associated with over-watering. Where the Leontief functional form defines yield perceptions, the water use is close to the

Table 3 Impact of yield expectations and water price on water use, realised returns, and the value of information regarding the water–yield relationship

Perceived functional form	Irrigation technology (spacing) Close (10 m × 10 m)		Medium (12 m × 12 m)		Wide (14 m × 14 m)		Difference† 12 × 12	14 × 14
Scenario 1. Water price (perceived social opportunity cost) is zero								
	Water use, ML/hectare							
Correct (Declining)	3.70	—	4.56	7.15	—	—	23%	93%
Plateauing	4.61	25%	6.21	36%	10.45	46%	35%	127%
Leontief	3.74	1%	4.62	1%	6.45	–10%	23%	72%
	Realised returns, $/crop ha							
Correct (Declining)	3940	—	3268	—	2165	—	–17%	–45%
Plateauing	3587	—	2790	—	1690	—	–22%	–53%
Leontief	3847	—	3226	—	2143	—	–16%	–44%
	Value of information‡, $/ha							
Plateauing yield	353	—	477	—	475	—	—	—
Leontief	93	—	41	—	23	—	—	—
Scenario 2. Water price (perceived social opportunity cost) is $200/ML								
	Water use§, ML/hectare							
Correct (Declining)	3.54	(–4%)	4.20	(–8%)	5.48	(–23%)	—	—
Plateauing	3.68	(–20%)	4.68	(–25%)	7.33	(–30%)	—	—
Leontief	3.74	(0%)	4.62	(0%)	6.45	(0%)	—	—
	Value of information, $/ha							
Declining yield	32	—	89	—	264	—	—	—
Plateauing yield	119	—	92	—	76	—	—	—
Leontief	32	—	89	—	264	—	—	—

†Difference compared to 10 m × 10 m spacing, ‡Difference in realised returns between correct and incorrect functional form, §Difference in water use compared to 'no water price' scenario in parentheses.

optimal level for the two most efficient systems, but 10 per cent lower for the widely spaced system. This is not to suggest that agronomic advice underestimates water requirements at these levels. In fact the rules of thumb used to determine these crop water requirements would also dictate that the 14 m × 14 m system was not of an acceptable uniformity standard and should not be used.

4.3 Impact of perceptions regarding yield–water relationship on realised returns

The realised returns achieved with sprinkler systems of different uniformity and impact of incorrect perceptions regarding the yield–water relationship are shown in Table 3. The first row shows realised returns where there is perfect information. These realised returns are net of the estimated per crop capital costs associated with each sprinkler system. The closest sprinkler spacing achieves the highest returns, $3940 per crop hectare, which is 17 per cent higher than the 12 m × 12 m spacing, and 45 per cent higher than the 14 m × 14 m design. These general relationships are also observed when the farmer makes water use decisions with incorrect information – they are always better off having closer sprinkler spacing. A measure of the short-run value of information regarding yield and uniformity is provided in the table, being the difference between realised returns under perfect information, and realised returns associated with water use decisions made under imperfect information. Where the farmer assumes yield plateaus and therefore uses substantially more water than the 'perfect information case' the realised impact on returns varies from $353 per crop ha for the 10 m × 10 m spacing to $475 for the 14 m × 14 m spacing. For the Leontief technology case, the deviation between returns relative to what could be earned with perfect information actually decreases as the distribution uniformity increases. This can be explained by the fact that the deviation in water use is relatively small for all sprinkler designs, and the gross margin curve (shown in Figure 2) gets flatter as uniformity declines.

4.4 Impact of water price on optimal scheduling

The effect of policy changes that internalise the social opportunity cost of water in irrigation decision making was examined by assuming a value for λ of $200/ML. In the following discussion this is referred to as the 'water price' scenario although this does not imply that volumetric charging is the policy prescription – in the Australian policy context a water market to signal the scarcity value within the irrigation sector of water allocated to agriculture is more likely. The assignment of a value for this analysis was arbitrary but does reflect the value of water traded in seasonal markets when water is relatively scarce and the higher valued uses are impacted at the margin (Brennan 2007). Results are shown in Table 3. For the perfect-information case, the water price has a greater impact for the widest sprinkler spacing and the lowest impact for the closest sprinkler spacing. This larger response for the system with the lowest distribution uniformity is the result of a relatively flat marginal productivity curve, which in turn is the result of 'averaging' the productivity effects of over- and under-watering (the same factor driving the flatter curve indicated in Figure 2).

When farmers operate under the perception that the yield plateaus at high application rates, the water price achieves a relatively larger reduction in water use. This is because the marginal productivity of water, at the point they are operating in the absence of a water price, is relatively flat. The introduction of a water price reduces water use by 20 per cent for the closest sprinkler spacing to 30 per cent for the widest spacing. The water price has no impact on water use under Leontief expectations, although it may cause a switching to other crops an option that was not considered in this analysis.

The realised losses associated with incorrect information on water productivity are shown in Table 3. The general effect of introducing a water price is to make information on water productivity relatively less valuable in the case where the farmer has 'plateauing yield' expectations. For example, the difference between realised returns was \$353 per hectare in the absence of the water market, and is only \$32 after the water market is introduced. This is because the water price invokes a much larger response when the farmer has plateauing yield expectations, bringing the two water use levels closer together after the introduction of the water price. The effect of the simulated water price on incentives to use water is substantially more important than the marginal productivity differences between the different functional forms.

In the case where the farmer holds Leontief expectations the value of information regarding water productivity is lower when the water price is zero. This is because under Leontief assumptions there is no adjustment in water use in response to high water costs, so the difference between expected profits under the baseline and the Leontief functional forms is greater when water use incurs a higher charge.

4.5 Benefits of adopting more efficient technology

The impact of perceptions regarding water productivity on the incentives for adoption depend not on the realised benefits associated with water use values, but the perceived benefits. The perceived gross margin values would be compared to the capital cost of the alternative systems and a decision to adopt would be expected to be made if the expected benefit of one system net of capital costs were higher than the other. The upper and lower bounds of the decision to adopt were shown in Equations (12) and (13). The benefits of adoption in this section are estimated for each of the poorer performing (wider spaced) sprinkler systems, where N is the 10 m × 10 m spacing.

4.6 Benefits of adoption, where water price is zero

The perceived benefits of adopting the most closely spaced sprinkler system are shown in Table 4. The first set of results show the realised and perceived

Table 4 Perceived and real benefits of adoption

	Perceived		Realised	
Perceived yield	Upper	Lower	Upper	Lower
Scenario 1. Water price (perceived social opportunity cost) is zero				
A. Benefits of adopting 10 m × 10 m when existing is 12 m × 12 m				
Perfect information	672	476	672	476
Imperfect information:				
Plateauing	67	–129	796	600
Leontief	27	–170	620	424
B. Benefits of adopting 10 m × 10 m when existing is 14 m × 14 m				
Perfect information	1775	1615	1775	1615
Imperfect information:				
Plateauing	236	77	1897	1738
Leontief	79	–80	1704	1545
Scenario 2. Water price (perceived social opportunity cost) is $200/ML				
C. Benefits of adopting 10 m × 10 m when existing is 12 m × 12 m				
Perfect information	822	626	822	626
Imperfect information:				
Plateauing	309	113	879	683
Leontief	202	6	796	600
D. Benefits of adopting 10 m × 10 m when existing is 14 m × 14 m				
Perfect information	2288	2128	2288	2128
Imperfect information:				
Plateauing	1116	956	2520	2360
Leontief	620	460	2245	2085

benefits relative to the sprinkler system with 12 m × 12 m spacing. When there is perfect information, the lower and upper ranges of benefits from adoption are $476 and $672 per crop hectare. The impact of imperfect information on the perceived benefit from adoption is substantially lower for all cases. This is because there is little perceived productivity impact associated with the closer sprinkler spacing. In contrast, the realised benefits are of similar magnitude to the realised benefits that arise when the farmer acts with perfect information. For example, there is only $120 per hectare difference between the realised benefits of adoption when the farmer acts with yield–plateauing expectations. This realised difference in benefits of adoption is the result of incorrect water scheduling, compared to optimal water scheduling, for the two different sprinkler designs: the farmer is actually even better off from adopting the closest sprinkler spacing if he is acting with incorrect information regarding water productivity. In comparison to a realised net benefit from adoption of between $600 and $796 per crop hectare, the perceived benefit from adoption is only $67 per hectare at best. If the farmer has sunk capital invested in the 12 m × 12 m spacing, there will be a perceived cost associated with adopting the closer sprinkler spacing because the additional capital cost is not sufficient to justify the small benefits from the lower water using system. This implies that a capital subsidy on equipment would be required to encourage adoption in the short run. Similar results are found for the Leontief case.

The results for the 14 m × 14 m case show similar trends. The benefit of adopting the closest sprinkler spacing is substantially higher than the 12 m × 12 m case. When the farm schedules irrigation with perfect information, the net benefit from adoption is \$1615–\$1775 for the 14 m × 14 m system compared to only \$476–\$672 for the 12 m × 12 m case. These benefits can be higher if the farmer schedules irrigation with incorrect information. However, the farmer will also perceive a higher benefit from adoption if operating under yield plateauing perceptions, although these perceived benefits are small in relation to the realised benefits of adoption. For the Leontief assumptions, there is little perceived benefit from adoption.

4.7 Benefits of adoption, water price is \$200/ML

The effect of introducing of a social water price on the perceived benefit from adopting the most closely spaced sprinkler system is shown in Table 4. Relative to the 12 m × 12 m system the introduction of a water price increases the benefit of adopting the 10 m × 10 m system by \$120 per hectare if the farmer is acting under perfect information. Also for the perfect information case, the water price increases the benefit of switching from the 14 m × 14 m system to the 10 m × 10 m system.

The water price also has a significant effect on the perceived benefits from adoption when the farmer is acting with imperfect information. This is particularly pronounced for the 14 m × 14 m case where the current sprinkler system has very poor uniformity. For example, when the farmer has Leontief yield expectations, the perceived benefit of adopting the 10 m × 10 m system is \$620 for the water price scenario, compared to \$79 in the base case.

5. Conclusions, limitations and policy implications

Much effort goes on identifying factors affecting adoption to determine how to encourage farmers to adopt more efficient water practices. This study used a bioeconomic modelling approach to demonstrate the influence of perceptions regarding water productivity on water-use decisions in the short run, as well as incentives to invest in more efficient sprinkler irrigation infrastructure. Based on an empirically derived water–yield relationship that incorporates an eventually declining marginal productivity of water, it was shown that the 'true' benefits associated with adopting more efficient sprinkler systems are strong and positive, as the benefit of a higher gross margin associated with more uniform application more than justifies the higher capital costs associated with closer sprinkler spacing.

These findings are contrasted by a low level of adoption of closer sprinkler spacing in the study area. The analysis of information and incentives presented here may go part of the way in explaining the low level of adoption. For example, lack of information regarding the shape of the water–yield relationships and the marginal productivity of water may contribute to low adoption. It was shown that when farmers perceive different yield functional forms, such as Mitscherlich or Leontief, there is little perceived benefit associated with adoption of more efficient systems because the perceived improvement in gross margin from a more uniform application does not outweigh the additional cost of investment. In cases where the perceived functional form is incorrect then there is scope for improved extension information regarding the water productivity to encourage the adoption of more efficient technology. This information would also lead to reduced water use in the short run (given existing irrigation equipment) and the potential for water savings are shown to be substantial. For example, water use is around 53 per cent higher when the farmer is acting with Mitscherlich expectations and has a poorly designed system with uniformity as in the case of the 14 m × 14 m spacing examined in this study. The impact on realised returns is also larger the poorer the distribution uniformity is, and for the 14 m × 14 m case an improvement in profits of more than 10 per cent is possible if farmers have better information on water productivity to guide irrigation scheduling decisions.

Lack of information about the social opportunity cost of water will also have a strong influence on both water-use decisions and on the incentive to adopt more water-efficient technology. In the example shown here, following the introduction of a social opportunity cost of water of $200/ML the incentive to adopt more uniform technology became large and positive for irrigators acting under Mitscherlich and Leontief expectations. These benefits were the result of the direct financial incentive to reduce water use. This implies that the economic efficiency problems associated with poor information regarding water productivity may be less important in determining incentives to adopt more efficient sprinkler systems when water is relatively scarce. The effect of differences in perceived functional form on water-use decisions in the short run was also less pronounced in the water-price simulations. This implies that the benefits of extension regarding crop scheduling decisions would be greater when there is no opportunity to use price instruments to guide water-use decisions, such as where it is difficult or costly to establish an effective water market, or when there is political distaste for volumetric charging of water to reflect social opportunity cost.

Results of empirical models of farmer decision making are always limited by how well the decision making problem has been represented, and a number of caveats to this analysis are worth noting. First, the objective function is assumed to be one of profit maximisation, and the economic life of capital was assumed to be the defined by asset life when calculating the annualised capital cost of investment. In the peri-urban context of the Gnangara Mound, urbanisation pressure has led to gradual shifting of irrigation farms over time, and some farmers now operate with the expectation that their farms will be rezoned for urban development in the future. Such farmers may not have the same outlook regarding productivity improvements, and may require a shorter time frame for capital investment decisions than was represented here. Another limitation of the study is the failure to account for inter-farm heterogeneity that will affect the water–yield relationship and will raise the transactions costs of information exchange. If this issue is substantial, then other policies to encourage adoption, such as subsidies on irrigation equipment or mandatory irrigation designs, may be more cost effective.

Results of the analysis are driven by the assumptions relevant to the case study area and may not directly apply elsewhere. For example, the strong incentive to adopt more uniform irrigation systems under profit maximising assumptions were driven by the strong yield incentive to reduce over-watering, which may not exist in other soil types where water and nutrient retention is better. The importance of the improvements in expected gross margin relative to the higher capital costs of closer sprinkler spacing might also be different in the case of field crops where gross margins are generally lower per unit of water applied. Nevertheless, the approach presented here allows for explicit examination of the relationship between the water production function, the performance of irrigation technology in delivering water to the crop, and the incentives to improve water use efficiency. The model could be calibrated to other field conditions in order to examine which policy measures might be used to encourage adoption of more efficient irrigation scheduling and more efficient sprinkler technology. The appropriateness of policy measures will be determined on a case-by-case basis but will include providing more research on the shape of the water production function, improving access to extension services, and correcting for market failures in water resource management.

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