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## Evaluating combined land conservation benefits from perennial pasture: lucerne (*Medicago sativa* L.) for management of dryland salinity and herbicide resistance in Western Australia\*

### Graeme J. Doole and David J. Pannell $^{\dagger}$

The inclusion of perennial pasture phases in cropping rotations has been widely promoted throughout Australia for reducing the incidence of dryland salinity. To a lesser extent, they have also been promoted to enhance the management of herbicideresistant weeds. No previous economic analysis of perennial pasture has considered both of these benefits. This study combines a dynamic linear programming model to estimate the magnitude of salinity-related benefits and a complex simulation model to assess the economics of herbicide-resistance management. We present a case study of the perennial pasture lucerne (Medicago sativa L.) in the Wheatbelt of Western Australia, where the weed annual ryegrass (Lolium rigidum Gaudin) is resistant to multiple herbicide groups. Sequences incorporating lucerne are the most profitable land use at the standard set of parameter values if (i) annual ryegrass is resistant to all selective herbicides, (ii) the water table is so shallow (approximately < 3.5 m deep) that frequent rotation with perennials is required to avert soil salinisation, (iii) sheep production is highly profitable, or (iv) there is a combination of less extreme cases. The value of perennial pasture is sufficient under these circumstances to overcome its high establishment cost and the displacement of multiple years of crop. Consideration of dryland salinity and herbicide resistance are about equally important in evaluating the economics of lucerne; neither should be neglected.

Key words: dryland salinity, herbicide resistance, lucerne.

<sup>\*</sup> The authors would like to thank Clinton Revell and Phil Ward for the provision of information. We would also like to acknowledge the valuable comments made by the Editor and two anonymous referees.

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#### 1. Introduction

Prior to extensive land clearance for agriculture, little rainfall progressed below the root zones of native vegetation in most of current agricultural areas of Australia. However, the replacement of this native vegetation with agricultural systems based on annual crops and pastures has substantially increased 'deep drainage' or 'recharge' (George *et al.* 1999).<sup>1</sup> High recharge occurs under annual plants as (i) low evaporation rates during the growing season limit evapotranspiration, (ii) the presence of minimal plant canopy between November and May constrains the use of out-of-season rainfall, and (iii) shallow root systems inhibit the interception of soil water. This causes water tables to rise, mobilising salt deposits and bringing them into the root zones of agricultural plants. This process, known as dryland salinity, has reduced the productivity of around two million hectares of previously productive agricultural land in Australia (Australian Bureau of Statistics 2002), including about one million hectares in Western Australia (McFarlane *et al.* 2004).

The main strategy for reducing recharge in Australia's extensive mixed-farming systems is the establishment of deep-rooted perennial plants in place of traditional annual crops and pastures. Perennial plants can grow in response to summer rainfall and create a dry soil buffer that can absorb recharge from annual plants grown in the vicinity or in subsequent years (Ward 2006). This buffer should ideally be managed to maintain saline water tables at least 2 m below the soil surface, so that the yield of annual plants is not compromised (Clarke *et al.* 2002).

Perennial trees, such as Tasmanian blue gums (*Eucalyptus globulus* Labill.), can significantly reduce deep drainage (George *et al.* 1999), but these are generally uneconomic in low-rainfall areas. In contrast, the use of regular phases of perennial pasture species, such as lucerne (*Medicago sativa* L.), to minimise recharge in crop sequences is a promising method for sustaining crop production in the Western Australian Wheatbelt (e.g. Latta *et al.* 2002). These pastures are sown in rotation with annual crops and limit deep drainage through creating a dry soil buffer that can absorb leakage beneath the subsequent crop phase. The profitability of incorporating perennial pastures in crop rotations is of central importance in determining the extent to which soil salinisation is abated throughout this region.

Numerous studies have reported, however, that rotations incorporating lucerne are generally only profitable if adopted over modest areas that are too small to confer substantial off-site benefits (see Ridley and Pannell (2005) and references therein). This follows strong theoretical and empirical

<sup>&</sup>lt;sup>1</sup> These terms refer to movement of water through the root zone and into groundwater, possibly resulting in a rise in the groundwater level. Simulation results from the Leakage/ Buffer model (Ward 2006) indicate that mean recharge in a deep, sandy soil in the Central Wheatbelt region of Western Australia is nearly 300 times greater than that experienced underneath native vegetation.

evidence that discharge at a catchment level can only be avoided if a large proportion of the catchment is planted to perennial plants. For example, George *et al.* (1999) identified that up to 70–80 per cent of some catchments in Western Australia must be planted with perennials to fully contain salinity at hydrological equilibrium. Worthwhile external benefits for salinity delay or abatement might be expected in some catchments if perennials could be established on 30–40 per cent of the total area, but even this lower range is high compared with the profitable proportions estimated in most regions in previous studies.

Apart from helping to reduce recharge, perennial pastures aid the management of herbicide-resistant weeds through broadening the range of weed treatments that can be applied (Doole 2008; Doole and Pannell 2008). Nonetheless, the profitability of perennial pastures has not been assessed in light of their combined value for the management of herbicide-resistant weeds and saline water tables. This current research addresses this gap in the literature. We present a detailed case study of the value of lucerne pasture for herbicide resistance and hydrological management in the Western Australian Wheatbelt. This builds upon the large number of studies that analyse the value of lucerne as a pasture legume and a source of feed for livestock (see Ridley and Pannell 2005) and recent analyses that consider its value for the control of herbicide-resistant annual ryegrass (*Lolium rigidum* Gaudin) (Doole 2008; Doole and Pannell 2008). This study includes all of those benefits, in addition to benefits related to salinity management.

The paper consists of two parts. First, a linear programming (LP) model is used to identify the most profitable strategy to address water table rise in the study region under a variety of scenarios. Second, output from this model is used to augment results from an investigation of herbicide resistance management (Doole and Pannell 2008) conducted with a detailed simulation model, which did not account for dryland salinity.

A model to analyse the profitable management of dryland salinity is developed in Section 2. In particular, we describe how this framework is used to estimate the cost accruing to the recharge occurring beneath each rotation explored by Doole and Pannell (2008). Output from the salinity model and its impacts on the economics of lucerne are presented and discussed in Section 3. Key conclusions are stated in Section 4.

#### 2. Model of dryland salinity management

This section consists of three parts. Section 2.1 describes a LP model that determines the change in profit associated with a millimetre change in the level of the saline water table. An increase in the level of the water table (i.e. one that becomes closer to the soil surface following recharge) decreases profit since it reduces future productive capacity on that soil. It is necessary to identify this value since maintaining a system based on annual plants incurs an opportunity cost in terms of decreased future production. Section

2.2 describes the parameter values used in this model. Section 2.3 identifies how the cost of recharge is integrated into model output from Doole and Pannell (2008).

#### 2.1 Model

This section presents a model to determine the optimal management of a saline water table in the Central Wheatbelt of Western Australia. This region is representative of the 40 per cent of wheat-producing areas in Western Australia that receive a mean annual rainfall of less than 325 mm and possesses hydrological systems and low land gradients typical of the Wheatbelt (Ridley and Pannell 2005). These factors help to ensure that this research is of direct relevance to many producers throughout this region. The general approach is also relevant to crop production across the southern states of Australia, and could be adapted for application in other regions.

The extent to which recharge management is profitable for a given farm is strongly influenced by the nature of the hydrological system beneath this production unit. Much of the Wheatbelt of Western Australia is very flat and has low hydrological transmissivity, and consequently much of it experiences little lateral movement of groundwater (Pannell *et al.* 2001). As an approximation, the groundwater systems of this region have been described as 'one dimensional', meaning that water primarily moves vertically. In this environment, the incidence of dryland salinity is mainly determined by management practices on site, rather than in surrounding areas. For example, George *et al.* (1999) found that the effect of tree plantations in this region usually extended at most a few tens of metres beyond the boundaries of the plantations. For this reason, the water balance model in this study depends solely on land use within the modelled field.

A hypothetical producer is assumed to maximise the value of a given area of land over a planning horizon of 100 years in this model. An extended period is appropriate since salinisation often develops slowly in the study region due to low rainfall, low land gradients, and low soil transmissivity (Pannell *et al.* 2001). The model is defined in discrete time to be consistent with the planting decisions of farmers and aid numerical analysis. A list of the key parameters incorporated in the model and subsequent analysis is presented in Table 1.

Time is defined over the closed interval t = [0, 1, 2, ..., T-1, T], where the terminal time period T = 99. Land is allocated between three enterprises in each period: one rotation consisting solely of annual crops  $(y_t)$ , one rotation incorporating perennial pasture  $(u_t)$ , and a saltland grazing system  $(z_t)$ . Therefore,  $y_t + u_t + z_t = 1$  for t = [0, 1, ..., T]. The area of land is normalised to one hectare as this aids comprehension, simplifies the calculation of parameters, and assists the integration of output with results from Doole and Pannell (2008).

A linear objective function is defined:

Parameter	Description	Standard value
Т	Terminal time	<i>T</i> = 99
t	Time periods	$t = [0, 1, 2, \dots, T-1, T]$
$y_t$	Area allocated to annual-based rotation	Determined in LP model
<i>u</i> <sub>t</sub>	Area allocated to perennial-based rotation	Determined in LP model
$Z_t$	Area allocated to saltland grazing system	Determined in LP model
r	Discount rate	r = 0.05
$\pi^c$	Gross margin for annual-based rotation	$\pi^c = $ \$79/ha/year
$\pi'$	Gross margin for perennial-based rotation	$\pi^{l} = $ \$66/ha/year
$\pi^{s}$	Gross margin for saltland grazing system	$\pi^s = $ \$22/ha/year
W <sub>0</sub>	Initial water table depth in millimetres	Varies with scenario
W <sub>T</sub>	Terminal water table depth	$w_T = 2000 \text{ mm}$
b	Stock of recharge before soil is salinised	Varies with scenario
	(i.e. $w_0 - w_T$ where $w_0 > w_T$ )	
$g^{c}$	Recharge under annual-based rotation	$g^c = 30 \text{ mm/year}$
$\overline{g}^l$	Recharge under perennial-based rotation	$g^{l} = 7.4 \text{ mm/year}$
$W_0^{ROT}$	Initial water table depth for a given rotation defined in the simulation model	Defined exogenously
N	Total level of recharge occurring over a given rotation	Measured in mm
λ	Marginal change in optimal profit due to a millimetre change in b	Determined in LP model
Ψ	Decline in profit that occurs over the length of a rotation because of recharge	Determined from $\lambda_i$ through $\Psi = \sum_{n=1}^{W_0^{ROT} + N} \lambda_i$
-ROT	Value of rotation determined by Doole and	Defined in $\frac{1}{2}$ Defined in $\frac{1}{2}$
$\pi_{ann}$	Pannell (2008) expressed as an annuity	
$\psi_{ m ann}$	Annual equivalent of $\psi$	Determined from $\psi$ through $\Psi = r \Psi ((1 + r)^{20}/((1 + r)^{20} - 1))$
π*	Net annual profitability of a rotation	$\pi^{*} = \pi^{ROT}_{ann} - \psi_{ann}$

 Table 1
 Description of key parameters used in the modelling analysis

$$\max_{y_t, u_t, z_t} J = \sum_{t=0}^{T} (1+r)^{-t} (\pi^c y_t + \pi^l u_t + \pi^s z_t),$$
(1)

where r is the discount rate,  $\pi^c$  is the annual gross margin for the rotation of annual crops,  $\pi^l$  is the annual gross margin for the rotation including perennial pasture, and  $\pi^s$  is the annual gross margin for the saltland grazing system.

This objective function is maximised subject to a constraint describing the permissible amount of recharge that may occur over the planning horizon before soil salinisation develops. This is described in the water table constraint:

$$b \ge \sum_{t=0}^{T} (g^{c} y_{t} + g^{l} u_{t}), \qquad (2)$$

where  $b = (w_0 - w_T)$ ,  $w_0$  is an exogenously-defined initial water table depth,  $w_T$  is an exogenously-defined terminal water table depth,  $w_0 > w_T$ ,  $g^c$  is the recharge occurring under the annual system, and  $g^l$  is the leakage occurring under the perennial-based system. All of these parameters are measured in

millimetres for ease of interpretation. It is assumed that the producer uses bores to gauge the height of the water table with certainty.

Wheat (*Triticum aestivum* L.) growth is generally affected when saline water tables are less than 1.8 m from the soil surface, compared with barley (*Hordeum vulgare* L.) which has a threshold of 1.5 m (Nulsen 1981). However, a water table shallower than 2 m will ascend to the surface quickly, irrespective of water use by plants, due to capillary action caused by evaporation. Consequently,  $w_T = 2000$  mm (i.e. 2 m). The constraint specified in Equation (2) is defined as an inequality as it may not be economically optimal for the producer to salinise the soil over the planning horizon. Incorporation of a fixed stock (*b*) in (2) highlights the equivalence between the exploitation of a non-renewable resource and the management of a one-dimensional saline water table.

The initial water table depth is defined so that  $w_0 > 2000$  mm. This parameter is varied in the following application to study the relationship between water table depth and the value of perennial pasture for salinity mitigation.

The gross margins for the annual- and perennial-based enterprises are always greater than that defined for the saltland grazing system in this study. This is appropriate since saltland grazing systems are generally less profitable than production on non-saline land. The  $z_t$  activity is consequently only selected in the model at the standard set of parameter values when the constraint (2) is binding (i.e. the time at which *b* is exhausted and soil salinisation develops). This is feasible in the model since the saltland grazing system incurs no recharge and therefore is not defined in Equation (2). This characteristic of the problem allows the endogenous determination of the optimal time at which saltland grazing systems should be adopted.

For simplicity, it is assumed that discharge from the aquifer is small relative to annual recharge, and so can be omitted from the problem. This assumption could easily be relaxed for other areas, but is appropriate for this application given the low land gradients and low soil transmissivity typical of the study region (Pannell *et al.* 2001).

The optimisation problem faced by the producer is consequently

$$\max_{y_t, u_t, z_t} J = \sum_{t=0}^{T} (1+r)^{-t} (\pi^c y_t + \pi^l u_t + \pi^s z_t),$$
(3)

subject to:

$$b \ge \sum_{t=0}^{T} (g^{c} \cdot y_{t})(g^{c}y_{t} + g^{l}u_{t}), \qquad (4)$$

$$y_t + u_t + z_t = 1$$
 for  $t = [0, 1, 2, ..., 1, T - 1, T]$ , (5)

$$y_t \ge 0, u_t \ge 0, z_t \ge 0$$
 for  $t = [0, 1, 2, \dots, T-1, T]$ , and (6)

$$T$$
 fixed. (7)

The trajectory of the water table may be recovered from this problem through the substitution of the optimal set of decision variables into the difference equation  $w_{t+1} - w_t = -g^c y_t - g^l u_t$  for t = [0, 1, 2, ..., T], where the variable  $w_t$  represents the depth of the water table (in millimetres) from the soil surface in year t. The initial condition for this process is the parameter  $w_0$ .

#### 2.2 Parameter values

This section presents the parameter values used in the LP model. The next section describes the way that the output from the LP model is used to manipulate results generated by Doole and Pannell (2008) from a complex simulation model. A real discount rate of 5 per cent is used in both models.

The rotation of annual crops is represented by a continual-cropping sequence given the high profitability of these systems in the absence of herbicide resistance. The gross margin is  $\pi_c = \$79$  ha/years. This is the mean gross margin calculated for a wheat–wheat–barley–lupin rotation in the resistance and integrated management (RIM) model<sup>2</sup> (Pannell *et al.* 2004), and is determined for an initial annual ryegrass density of average magnitude (500 seeds m<sup>-2</sup>) and no initial herbicide resistance.

The rotation including perennial plants is a lucerne–lucerne–lucerne– wheat–wheat–barley sequence (Doole and Pannell 2008). Half of the rotation consists of perennial pasture as this ensures minimal leakage under standard circumstances. Its profitability is calculated for mean sheep gross margins ( $\pi^{\text{sheep}}$ ) of \$10 per dry sheep equivalent (DSE), \$15/DSE, \$20/DSE, and \$25/ DSE. A dry sheep equivalent is a standard measure of stocking density representing a wether of average size. The annual gross margin accruing to the perennial-based system is simply the annualised gross margin earned over the six-year rotation. The RIM model is used to identify  $\pi^{l} =$ \$54/ha/year for  $\pi^{\text{sheep}} =$ \$10/DSE,  $\pi^{l} =$ \$66/ha/year for  $\pi^{\text{sheep}} =$ \$15/DSE,  $\pi^{l} =$ \$79/ha/year for  $\pi^{\text{sheep}} =$ \$20/DSE, and  $\pi^{l} =$ \$91/ha/year for  $\pi^{\text{sheep}} =$ \$25/DSE. These results are calculated for an initial weed density of 500 seeds/m<sup>2</sup> and no initial herbicide resistance.

<sup>&</sup>lt;sup>2</sup> The RIM model is a complex deterministic simulation model incorporating a sophisticated biophysical model of annual ryegrass and an economics module. These are integrated so that the agronomic and economic implications of alternative weed management strategies on a typical soil in a mixed-farming system in the Central Wheatbelt of Western Australia can be determined. Herbicide resistance is incorporated in this model through the manipulation of the number of selective herbicide applications that may be used prior to this chemical being no longer effective against ryegrass. Resistance present at the beginning of the horizon is referred to as 'initial resistance' in the following to distinguish it from herbicide resistance that develops during the planning period. Selective herbicides are described in the RIM model according to the Herbicide Resistance Action Committee (Kramer and Schirmer 2007) system. The number of applications of each mode of action available to a producer before resistance develops in the standard model is two doses of each type of Group A herbicide ('fop' and 'dim'), two doses of Group B herbicide, five doses of Group C herbicide, and five doses of Group D herbicide.

It costs approximately \$225/ha to establish a saltland grazing system incorporating a 5-m alley of saltbush (Atriplex spp.) and a 15-m alley of improved annual pastures incorporating salt-tolerant balansa clover (Trifolium michelianum Savi), tall wheat grass (Thinopyrum elongatum L.), and puccinellia (Puccinellia ciliata Bor.) (O'Connell et al. 2006). This establishment cost is denoted as  $c^{\text{sbest}}$ . This cost is amortised over 20 years at a real interest rate of 5 per cent. This yields  $c_{ann}^{sbest} = $18.05$ . This cost is defined in each year that the saltland grazing system is used as these systems require ongoing maintenance to ensure that adequate productivity is sustained. Any bias introduced through the employment of this assumption is reduced through discounting given the length of the planning horizon and the general adoption of saltland farming systems towards the end of the planning period. An annual fertiliser cost of \$20/ha is also specified (O'Connell et al. 2006). Saltland grazing systems typically support a grazing rate of 4 DSE ha/year (Saltland Pastures Association 2006). Thus,  $\pi^s = \frac{2}{ha}/year$  for  $\pi^{sheep} = \frac{10}{DSE}$ ,  $\pi^s = \frac{22}{ha}/year$ for  $\pi^{\text{sheep}} = \$15/\text{DSE}$ ,  $\pi^s = \$42/\text{ha/year}$  for  $\pi^{\text{sheep}} = \$20/\text{DSE}$ , and  $\pi^s = \$62/\text{ha/year}$ for  $\pi^{\text{sheep}} = \$25/\text{DSE}$ .

The profitability estimates of Doole and Pannell (2008) were determined for an average sandplain soil; thus, to minimise bias, the recharge figures for the LP model presented above are derived from studies incorporating a similar soil type. O'Connell (2003) identified an estimate of  $g^c = 20$  mm/year for an average sandplain soil in the study region; however, Asseng *et al.* (2001) identified  $g^c = 39$  mm/year for the same soil type in that location. The rate of recharge occurring under annual crops is therefore defined as the rounded mean of these two values ( $g^c = 30$  mm/year).

The Leakage/Buffer model (Ward 2006) is used to identify mean recharge  $(g^l)$  for the rotation including perennial plants on a sandplain soil in the study region. Each three-year phase of lucerne pasture is assumed to form a buffer of dry soil capable of absorbing 100 mm of recharge from subsequent crops before leakage begins to reach the saline water table. This buffer size is the average volume observed in field trials throughout southern Australia (Ward 2006). The calculation using the Leakage/Buffer model yields  $g^l = 7.4$  mm/year.

A two-phase simplex method in GAMS/MINOS 5.5 (Murtagh and Saunders 1998) is used to solve the LP problem posed by Equations (3–7).

#### 2.3 Evaluating the profitability of alternative rotations

Doole and Pannell (2008) use the RIM model to determine the profitability of a number of common rotations taking into account the implications of different levels of herbicide resistance. This section describes how these values are modified in this study to reflect the hydrological impacts of each sequence. The rotations studied here are listed in Table 2.

The value of each rotation for hydrological management is specific to a given initial water table depth  $w_0^{ROT}$  since this is an important determinant

Rotation	Reference term
Lupin–wheat–barley	С
Serradella-wheat-wheat-barley	S+3C
Serradella-wheat-wheat-barley-lupin-wheat-wheat-barley	S+7C
Serradella-serradella-wheat-wheat-barley-lupin-wheat- wheat-barley	3S+7C
Lucerne-lucerne-wheat-wheat-barley Lucerne-lucerne-wheat-wheat-barley-lupin-wheat-wheat-barley	3L+3C 3L+7C

 Table 2
 Candidate rotations and associated reference terms

of the capacity of a producer to continue traditional crop production. The total level of recharge occurring over the duration of each rotation (N) from this initial point is determined from the following relationships. Leakage of 30 mm is assumed to occur underneath each year of annual crop, as described in Section 2.2. Deep-rooted annual pastures, such as serradella (*Ornithopus sativus* L.), may use more soil water than annual crops (Tennant and Hall 2001). However, these land uses incur similar recharge when they are sown at the same time (Fillery and Poulter 2006). Accordingly, recharge under serradella pasture in the year it is sown is set at  $g^c$ . In comparison, regenerating serradella pasture (i.e. that in the second and third years of the 3S+7C rotation) (Table 2) incurs recharge of 20 mm/year as it emerges earlier than annual crops. The disparity between this estimate and  $g^c$  is consistent with results from field experiments reported by Fillery and Poulter (2006).

The buffer size established by a three-year lucerne phase is 100 mm (see Section 2.2). Deep drainage underneath each rotation incorporating lucerne is determined through the simple dynamic rule employed for recharge in the Leakage/Buffer model (Ward 2006). This is described in the following equations: (1) if  $G_t^{nb} \ge B_t$  then  $G_t = G_t^{nb} - B_t$  and  $B_{t+1} = 0$ , and (2) if  $B_t > G_t^{nb}$  then  $B_{t+1} = B_t - G_t^{nb}$  and  $G_t = 0$ , where  $G_t^{nb}$  is drainage under annual crops in the absence of a buffer in year t,  $B_t$  is the size of the buffer, and  $G_t$  is actual annual recharge occurring below the annual crop. All of these variables are measured in millimetres.

This paragraph describes the calculation of an annuity representing the cost of recharge accruing to each rotation. The shadow price  $\lambda$  for the water table constraint (2) computed for the model described in Section 2.1 represents the marginal change in optimal profit (in net present value terms) due to a millimetre change in the stock of permissible recharge (b). As the shadow price is sensitive to current water table depth, calculating the impact of non-marginal changes in depth requires the summation of shadow prices over the relevant range of depths. The decline in profit due to recharge that occurs over a rotation, denoted  $\Psi$ , may be approximated by  $\Psi = \sum_{i=w_{ROT}^{w_{ROT}} \lambda_i$ , where N is the level of recharge that occurs over the duration of a rotation and  $\lambda_i$  denotes the shadow price accruing to a millimetre of recharge at *i*. The

shadow prices  $(\lambda_i)$  are obtained through the solution of an individual linear program for each level of *b* over the interval b = [1, 2, ..., 3000], where  $b = w_0 - w_T$ ,  $w_0 = [2001, 2002, ..., 5000]$ ,<sup>3</sup> and  $w_T \equiv 2000$ . The annualised equivalent of  $\psi(\psi_{ann})$  is derived according to the standard rule, that is,  $\Psi_{ann} = r\Psi((1 + r)^{20}/((1 + r)^{20} - 1))$  given that horizon length is 20 years in the RIM model. The net profitability of each rotation considered by Doole and Pannell (2008) once its impact on hydrological management is monetarised is  $\pi^* = \pi_{ann}^{ROT} - \Psi_{ann}$ , where  $\pi_{ann}^{ROT}$  is the value of the rotations calculated by these authors expressed as an annuity.

According to mathematical-programming theory, the shadow price of the water table constraint is computed with the condition that the saline water table is managed optimally over the planning horizon following the adjustment in water table depth (Bazaraa and Shetty 1993). Therefore, maintaining fixed rotations as defined by Doole and Pannell (2008), and not that optimal land allocation identified by LP, introduces some bias into the calculation of  $\psi$  for each rotation. Nevertheless, this heuristic approach is retained as (i) it probably introduces little bias given the low value of  $\lambda_i$  over most values of  $w_0^{ROT}$  and (ii) suitable alternative approaches are difficult to conceptualise and implement.

#### 3. Results and discussion

This section presents results from the LP model and investigates the implications of the cost of recharge for the profitability of the rotations evaluated by Doole and Pannell (2008).

#### 3.1 Standard model results

The LP model is used to determine the relationship between permissible recharge and profitable land use allocation for a number of different initial water table depths. The optimal allocation consists of the sole use of annual crops until the stock of permissible recharge is so low that the perennial-based system must be adopted to prolong grain production. The first corner in each trajectory in Figure 1 corresponds to this change in land use. It is optimal to incorporate lucerne in the rotation at a water table depth of 2318 mm at  $w_0 = 2500$  mm, 2330 mm at  $w_0 = 3500$  mm, and 2162 mm at  $w_0 = 4500$  mm. The high amount of permissible recharge available at  $w_0 = 4500$  mm allows

<sup>&</sup>lt;sup>3</sup> The highest initial water table depth considered is  $w_0 = 5000$  mm since  $w_T = 2000$  mm and 100 years  $\times$  30 mm/year (the maximum feasible level of recharge) yields 3000 mm of recharge over the planning horizon. It is profitable to allocate all land to annual crops in each year of the planning horizon at  $w_0 = 5000$  mm. Annual-based rotations are also more profitable at the deeper initial water tables considered in the following analysis. These outcomes reflect lower incentives for recharge reduction due to the extended period it will take for soil salinisation to develop. Thus, results identified for the higher end of the feasible range for  $w_0$  incorporated in this study give a good indication of profitable actions at deeper water tables.



**Figure 1** Optimal trajectories of the saline water table computed for different initial water table depths. The evolution of the water table is determined by land allocation between annual crops and perennial pasture, with saltland grazing systems adopted at a depth of 2000 mm.

annual cropping to be maintained over the majority of the planning horizon; thus, the use of lucerne to extend the productive life of the farming system can be deferred. This motivates greater degradation under annual cropping before the perennial-based system is used.

The saltland grazing system is adopted when the water table reaches 2 m (2000 mm). This corresponds to the second corner in the trajectories for  $w_0 = 2500$  mm and  $w_0 = 3500$  mm in Figure 1. Saltland grazing systems are never adopted at  $w_0 = 4500$  mm since the terminal water table depth is reached only in the final period.

The number of years allocated to each system under optimal management is presented in Table 3. The optimal proportion of the horizon allocated to annual crops increases with the permissible amount of recharge (Table 3). This reflects the high profitability, but significant leakage, of annual-based rotations. The shadow price of the water table constraint decreases with an increase in the permissible amount of recharge (b) as Equation (4) consequently restricts production to a lesser degree. This lower shadow price reduces the user cost accruing to the employment of a given duration of annual cropping, subsequently promoting a greater allocation of land to the annual-based rotation. In contrast, the saltland grazing system increases in importance at shallower initial water tables (Table 3). The perennial-based sequence is a transitory phase adopted between the exploitative cropping phase and the onset of salinisation. This follows directly from its low level of recharge and intermediate profitability.

The optimal land allocation is presented in Table 4 for a number of different parameter values at  $w_0 = 2500$  mm. The saltland grazing system is important if recharge under the lucerne rotation ( $g^l$ ) is non-zero, as both the annual- and perennial-based systems promote water table rise in this instance. Recharge may occur under perennial pasture, especially after extreme rainfall

Initial water table depth (mm)	Years of annual crop	Years of the perennial system	Years of the saltland system
2500	5	43	52
3500	39	46	15
4500	77	23	0

**Table 3** Allocation of land between annual cropping, the perennial-based rotation, and the saltland grazing system at different initial water table depths

Chase areas	Annual rechar	Annual recharge occurring under the perennial-based system (mm)							
margin (\$/DSE)	0	2.5	5	7.4					
10	17-83-0†	11-73-16	9-47-44	8-36-56					
15	17-83-0	10-72-18	7-67-26	5-43-52					
20	16-84-0	8-92-0	1-93-6	0-67-33					
25	17-83-0	10-90-0	0-100-0	0-67-33					

**Table 4** Optimal land allocation at  $w_0 = 2500 \text{ mm}$ 

<sup>†</sup> This denotes the number of years allocated to annuals-perennials-saltland. For example, 17–83–0 denotes a land use allocation of 17 years to annual crops, 83 years to the perennial-based system, and 0 years to the saltland grazing system.

events, because water can bypass soil pores and move rapidly down the soil profile. In comparison, the rotation incorporating lucerne becomes less attractive as  $g^l$  increases. The primary importance of the perennial-based system at high sheep gross margins is also evident in Table 4.

The shadow price of recharge  $(\lambda_i)$  is presented in Figure 2 for  $i = [2001, 2002, \ldots, 4000]$  for a number of alternative discount rates. The shadow price increases as the initial water table approaches the point at which traditional agriculture cannot be maintained (2 m) (Figure 2) as this necessitates greater use of the less-profitable perennial and saltland systems over the planning period. The shadow price increases at a lower discount rate (for a given water table depth) since this enhances the importance of future production, and this provides a greater incentive for resource conservation.

#### 3.2 Combined value for weed and water table management

This section investigates how the profitability of the rotations listed in Table 2, determined in Doole and Pannell (2008), changes when the cost of recharge occurring beneath them is considered. The net profitability of these rotations ( $\pi^*$ ) is reported in Table 5 for a number of initial water table depths  $w_0^{ROT}$ . The lowest initial water table depth (2601 mm) in Table 5 is the minimum viable depth that an annual system requires over the 20-year horizon represented in the RIM model as 2001 mm + (20 × 30 mm) = 2601 mm



Figure 2 Optimal trajectories of the shadow price for alternative real discount rates (r). The shadow price is the change in net present value accruing to a millimetre change in the total recharge that may occur before the onset of soil salinisation.

		$w_0^{ROT} = 2601 \text{ mm}$		w <sub>0</sub> <sup>RO</sup> 3500	T = mm	$w_0^{ROT} = 4500 \text{ mm}$	
Rotation	N	$\Psi_{ m ann}$	$\pi^*$	$\Psi_{ m ann}$	$\pi^*$	$\Psi_{ m ann}$	$\pi^*$
С	600	78	1	8	71	2	77
S+7C	600	78	-1	8	69	2	75
S+3C	600	78	-3	8	67	2	73
3S+7C	560	60	15	7	68	1	74
3L+7C	220	9	63†	2	70	0	72
3L+3C	7.4	0	55	0	55	0	55

**Table 5** Rotation value  $(\pi^*)$  for a range of initial water table depths

† A shaded cell represents the most valuable rotation at that initial level of the water table.

given that  $g_c = 30$  mm/year. The remaining depths represent deeper water tables at which the economic incentives for recharge reduction are somewhat less pronounced.

The continuous-cropping rotation is the most profitable rotation at the two deeper water tables considered in Table 5; here, the initial water table is sufficiently deep for the future implications of current recharge to not influence planting decisions in the near-term. However, annual-based systems are penalised greatly at  $w_0^{ROT} = 2601$  mm as the cost of recharge increases as the terminal water table depth ( $w_T = 2000$  mm) is approached. This demonstrates the high opportunity cost accruing to the maintenance of annual-based rotations at shallow water tables given the economic importance of the perennial-based and saltland systems in these circumstances. The negative annuity occasionally realised for rotations incorporating solely annual plants represents that the onset of salinisation is never delayed through the adoption of perennials in these sequences.

The 3L+7C rotation is the most profitable system at  $w_0^{ROT} = 2601$  mm as it incorporates a long cropping phase and sufficient lucerne for considerable recharge reduction. These dual benefits also contribute to its relatively high profitability at  $w_0^{ROT} = 3500$  mm. In comparison, the 3L+3C sequence is attractive at  $w_0^{ROT} = 2601$  mm due to its high value for recharge reduction, but becomes relatively less valuable as the initial water table gets deeper as this rotation only contains a small cropping component. Additional analysis reveals that the 3L+7C sequence is more profitable than the 3L+3C rotation at  $w_0^{ROT} = 2409$  mm and deeper. However, continuous-cropping is more profitable than the 3L+7C rotation at  $w_0^{ROT} = 3401$  mm mm and deeper as the cost of recharge is of insufficient magnitude here to justify the regular employment of deep-rooted perennial pasture. These arguments reinforce the direct relationship between water table depth and the value of lucerne for recharge reduction.

#### 3.3 Implications of a change in annual recharge

There is considerable uncertainty in the estimated level of recharge occurring underneath annual crops and pasture in the Central Wheatbelt of Western Australia. A lower rate of  $g^c$  decreases the cost of recharge since annual plants may be used at a greater intensity without incurring more total recharge than that sustained at a higher level of  $g^c$ . This decline in the cost of recharge may be significant; for example,  $\psi_{ann}$  in the C rotation declines by nearly 75 per cent as leakage under annuals is reduced from  $g^c = 30$  mm/year to  $g^c = 20$  mm/year at  $w_0^{ROT} = 2601$  mm. Accordingly, the threshold at which annual cropping becomes more profitable than perennial-based rotations decreases substantially from  $w_0^{ROT} = 3401$  mm to  $w_0^{ROT} = 2820$  mm at  $g^c = 20$  mm/year.

System		$g^{c} = 20$	mm/year		$g^c = 40 \text{ mm/year}$				
	N	$\pi_{2601}$	$\pi_{3500}$	$\pi_{4500}$	N	$\pi_{2801}$	$\pi_{4000}$	$\pi_{5000}$	
C	400	50	76	79	800	48	72	77	
S+7C	400	48	74	77	800	46	70	75	
S+3C	400	46	72	75	800	44	68	73	
3S+7C	360	51	72	75	760	49	68	73	
3L+7C	80	68†	72	72	360	64	70	71	
3L+3C	0	55	55	55	20	55	55	55	

**Table 6** Rotation value  $(\pi^*)$  for a range of initial water table depths and different levels of leakage beneath annual plants

† A shaded cell represents the most valuable rotation at that initial level of the water table.

The magnitude of  $\pi^*$  and the rankings reported for the six rotations in Table 6 are similar for  $g^c = 20$  mm/year and  $g^c = 40$  mm/year. However, the initial water tables represented for  $g^c = 40$  mm/year are substantially greater given the large increase in total recharge (N) occurring underneath each sequence

		Initial water table depth (mm)									
groups	2601	3000	3500	4000	4500	5000					
None A A, B A, B, C	3L+7C† 3L+7C 3L+7C 3L+7C 3L+7C	3L+7C 3L+7C 3L+7C 3L+7C 3L+7C	C 3L+7C 3L+7C 3L+7C 3L+7C	C C/S+3C 3S+7C 3S+7C 3I +7C	C C/S+3C 3S+7C 3S+7C 3I +7C	C C/S+3C 3S+7C 3S+7C 31+7C					

**Table 7** Profit-maximising rotation for different degrees of herbicide resistance and initial water table depths at a sheep gross margin of  $$15 \text{ DSE}^{-1}$ 

† A shaded cell represents a scenario in which a perennial-based rotation is the most profitable sequence.

(Table 6). For  $g^c = 40$  mm/year, the C rotation only becomes more valuable than the 3L+7C system at  $w_0^{ROT} = 3609$  mm and deeper, a threshold that is 6 per cent higher than that identified in the standard model. This reinforces the presence of a direct positive relationship between the rate of leakage under annual crops and the value of perennial pasture for recharge management.

#### 3.4 Implications of herbicide resistance

Table 7 presents the most profitable rotation for a variety of circumstances that vary according to initial water table depth and initial state of herbicide resistance. Annual-based systems are profitable at (i) deep initial water tables, and (ii) where less severe levels of (initial) herbicide resistance are observed (Table 7).

The adoption of three-year phases of serradella pasture (an annual) is justified at deeper initial water tables when moderate levels of herbicide resistance are present; for example, where annual ryegrass is resistant to Group A–B or Group A–C chemicals and saline water tables are deeper than 3.5 m. The 3L+7C system is the most profitable sequence at water tables of 3.5 m depth and shallower in the presence of any form of initial herbicide resistance. Moreover, this sequence is the most profitable rotation at any depth when annual ryegrass is resistant to Group A–D chemicals in Year 1 (Table 7). In this circumstance, the value of perennial pasture for weed management is sufficiently enhanced to compensate for its displacement of multiple years of crop and its high establishment cost (Doole 2008; Doole and Pannell 2008).

#### 3.5 Implications of a change in relative profitability

The most profitable rotations for a range of scenarios are presented in Table 8. The optimal rotations identified by Doole and Pannell (2008) are those reported for an initial water table depth of 4500 mm for each level of livestock profitability in Table 8. Here, the water table is sufficiently deep for

A, B, C

All

3L+7C

3L+7C

3L+7C

3L+7C

Resistant groups	$\pi^{ ext{sl}}$	heep = 10/DS	SE	π	sheep = \$15/C	DSE	$\pi^{s}$	heep = 20/D	SE	$\pi^{s}$	heep = 25/D	SE	
	Initial water table (mm)		Initial water table (mm)			Initial water table (mm)			Initial water table (mm)				
	2601	3500	4500	2601	3500	4500	2601	3500	4500	2601	3500	4500	
None	3L+7C†	С	С	3L+7C	C N + 7C	C	3L+7C	3S+7C	3S+7C	3L+7C	3L+7C	3L+7C	
A	3L+/C	C	C	3L+7C	3L+7C	C/S+3C	3L+7C	3L+7C	3S+7C	3L+7C	3L+7C	3L+7C	
A, B	3L+7C	3L+7C	С	3L+7C	3L+7C	3S+7C	3L+7C	3L+7C	3S+7C	3L+7C	3L+7C	3L+7C	

3S+7C

3L+7C

3L+7C

3L+7C

3L+7C

3L+7C

3S+7C

3L+7C

3L+7C

3L+7C

3L+7C

3L+7C

Table 8 Profit-maximising rotation for alternative sheep gross margins, degrees of herbicide resistance, and initial water table depths

3L+7C

3L+7C

† A shaded cell represents a scenario in which a perennial-based rotation is the most profitable sequence.

3L+7C

3L+7C

3S+7C

3L+7C

the value of each rotation to be determined independent of its contribution to the development of dryland salinity (see Section 3.2). The value of lucerne is understandably amplified as the initial water table decreases in depth (Table 8), highlighting the importance of considering hydrological impacts in bioeconomic models used to assess the profitability of perennial pasture.

Table 8 displays that the high value of perennial pasture at low initial water table depths or in the presence of severe herbicide resistance is invariable to substantial changes in the profitability of livestock production. For example, even if the sheep gross margin is reduced to \$10/DSE, the 3L+7C rotation remains the most profitable sequence at  $w_0^{ROT} = 2601$  mm and when resistance has developed to Group A–D herbicides (Table 8). The 3L+7C sequence is also the most valuable rotation at  $w_0^{ROT} = 3500$  mm in the presence of any initial resistance at  $\pi^{\text{sheep}} = \$15/\text{DSE}$  and above. Herbicide resistance and hydrological management appear to be as important as each other in determining the profitability of perennial pasture since either a shallow water table or severe resistance is sufficient to justify the high establishment cost of lucerne.

However, a change in the profitability of livestock production alters the composition of the optimal annual-based rotations at the deeper initial water tables represented in Table 8. At  $\pi^{\text{sheep}} = \$10/\text{DSE}$ , in the absence of severe herbicide resistance, the continuous-cropping sequence is the most valuable system at the deeper water tables considered. This reflects the low relative value of rotations incorporating annual pasture in this scenario. In contrast, three-year phases of serradella pasture are most profitable at  $\pi^{\text{sheep}} = \$20/\text{DSE}$  when light to moderate levels of herbicide resistance are present and the water table is sufficiently deep (Table 8).

#### 4. Conclusions

There has previously been little effort to estimate the value of lucerne for prolonging the productive capacity of dryland cropping systems in Western Australia through recharge reduction. This is very surprising given the key role of this species for the prevention of dryland salinity (Ward 2006) and the opportunity cost accruing to the maintenance of annual-based rotations at shallow water table depths. This analysis presents a method to estimate the value of lucerne for recharge reduction, which is used to extend previous research into the worth of perennial pasture for the control of herbicide-resistant annual ryegrass.

This research identifies that it is profitable to incorporate lucerne in rotations if:

- 1. annual ryegrass is resistant to Group A–D chemicals;
- 2. the water table is around 3.5 m deep or shallower;
- 3. sheep production is highly profitable (i.e. around  $\pi^{\text{sheep}} =$ \$25/DSE); or
- 4. a combination of less extreme cases of herbicide resistance and water table depth are considered simultaneously.

Only in these circumstances is the value of perennial pasture sufficiently enhanced to justify its high establishment cost and its displacement of multiple years of crop.

In reality, lucerne is typically only seen as a profitable addition to crop rotations in most areas of the Central Wheatbelt in cases where crop production is affected by the rise of saline water tables and/or the onset of severe herbicide resistance. This use of perennial pasture in systems at crisis point is consistent with model output, but disregards the important preventative role that lucerne can potentially play. This study highlights that the joint consideration of lucerne's benefits for weed and water table management render it a profitable option for adoption prior to the point that many producers perceive it to be valuable. This reinforces the need for land managers to consider the user cost accompanying annual crop production, while recognising lucerne's potential to offset this degradation.

Nonetheless, the future expansion of perennial pastures in the Central Wheatbelt is threatened by a number of environmental and market realities. First, a strong mining sector has increased competition for labour, increasing the cost of the intensive livestock management required to maximise the productivity of perennial pastures. Second, high grain prices currently limit the degree to which producers are willing to allocate land to pasture, even if this will allow the extension of future cropping activity. Third, lucerne production is limited on poorly-drained or acid soils, both of which are found throughout the Central Wheatbelt. Finally, annual rainfall is extremely sporadic in this region. This can harm lucerne establishment and complicate feed budgeting. On the other hand, the value of lucerne pasture for recharge reduction may be expected to increase if the seasonal and annual distribution of rainfall is accounted for (Ward 2006), as lucerne provides a hedge against that source of uncertainty. The extent to which these factors affect the findings of this study are ultimately empirical and worthy of further research.

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