Role and value of including lucerne (*Medicago sativa* L.) phases in crop rotations for the management of herbicide-resistant *Lolium rigidum* in Western Australia

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Abstract. Use of lucerne (*Medicago sativa* L.) pastures in crop rotations has been proposed as a method to enhance weed management options for growers facing herbicide resistance in Western Australia. An existing model for analysing herbicide resistance in the important crop weed annual ryegrass (*Lolium rigidum* Gaud.) is consequently extended to include lucerne, used for grazing by a sheep enterprise. Seven rotational options are analysed, including various combinations of lucerne, annual pastures, and crops. Lucerne provides additional weed management benefits across the rotation, but in the region studied these benefits are only sufficient to make lucerne rotations the most profitable option in situations where ryegrass is resistant to multiple herbicide groups, and/or livestock prices are very high.

Key words. Herbicide resistance, integrated weed management, economics, weed population dynamics.

1. Introduction

In recent years, farmers in Western Australia have been encouraged to include phases of lucerne (*Medicago sativa* L.) pasture within their crop production systems (Latta et al., 2001; Pannell and Ewing, 2006). Lucerne offers the prospect of enhancing the management of major crop weeds. Most importantly, it is likely to assist in the control of herbicide-resistant annual ryegrass (*Lolium rigidum* Gaud.) as it permits the use of a broader range of control strategies to exhaust weed seedbanks. Primary methods of control that may be implemented during a perennial pasture phase are grazing, hay and silage production, mowing, sterilisation of weed seed through the application of a non-selective herbicide to flowering plants (spray-topping), and the use of non-selective herbicides to kill the entire pasture prior to weed seed-set (brown-manuring) (Powles and Bowran, 2000). In addition, lucerne has been promoted for its role in preventing soil degradation arising from dryland salinisation (e.g., Pannell and Ewing, 2006; Ward et al., 2006).

Past analyses of the economics of lucerne have focused on its role as a feed supply, and have not considered its particular contributions to weed management (e.g., Bathgate and Pannell, 2002; Kingwell et al., 2003). The objective of this research is to investigate the profitability of a lucerne pasture phase, relative to alternative systems available to producers in the central wheatbelt of Western Australia, when its benefits for the management of herbicide-resistant weeds are considered. This provides valuable insight into the profitable integration of lucerne pasture phases (and the forms of weed contol implemented therein) with practical integrated weed management (IWM) strategies currently employed in this region. This study extends recent research indicating the high profitability of an annual pasture plant, French serradella (*Ornithopus sativus* Brot. cv.

Cadiz), for the control of herbicide-resistant weeds in Western Australian farming systems (Doole and Pannell, 2007).

The research problem addressed here is complex, involving the (a) dynamics of weed populations, (b) dynamics of herbicide-resistance development, (c) alternative crop and pasture options in many possible sequences, (d) competitive effects of weeds, (e) phytotoxic effects of treatments, (f) many possible weed management strategies, and (g) economic consequences. The complexity makes it difficult for farmers to assess alternative strategies through trialling, and this may inhibit the adoption of new practices (Pannell et al., 2006). Field experiments have a limited role in the development of robust management strategies, since there are too many possible strategies to physically trial. For these reasons, the study is based on bioeconomic modelling, integrating experimental and other information into a systems analysis. This multidisciplinary approach is important given the economic implications of on-farm weed management, but its intrinsic links to agronomic, biological, and chemical processes.

Section 2 includes descriptions of the model, the weed control options and the alternative rotations used to determine the relative profitability of sequences containing lucerne pasture. The results of the analysis are presented and discussed in Section 3. Key findings are summarised in Section 4.

2. Model

2.1 Model description

This application employs the resistance and integrated management (RIM) model to investigate the profitability of alternative IWM strategies to control herbicide-resistant annual ryegrass on a single field in the central wheatbelt of Western Australia (Pannell et al., 2004). This description of the model is based on typical explanations of the RIM model in the existing literature (e.g., Pannell et al., 2004; Doole and Pannell, 2007). The RIM framework is a deterministic simulation model representing the multiple-cohort dynamics of ryegrass plants and seeds, their interactions with crops and pastures, and the effects of a broad range of weed control strategies (see Section 2.2). The model allows the simulation of management strategies over a twenty-year period to capture the dynamic nature of weed populations and resistance development.

The representation of the onset of herbicide resistance is simple but realistic (Pannell et al., 2004). Each herbicide mode-of-action can only be used a limited number of times in the model before resistance occurs. For this application, the assumed numbers of applications of each selective herbicide group available before resistance develops are as follows: 2 doses of each type of ACCase inhibitor herbicides ("fops" and "dims", or Group A in the Herbicide Resistance Action Committee system (Kramer and Schirmer, 2007)), 2 doses of sulfonylurea herbicides (e.g., chlorulfuron, Group B), 5 doses of photosynthesis inhibitor herbicides (e.g., simazine, Group C), and 5 doses of dinitroanaline herbicides (e.g., trifluralin, Group D). (However, these assumptions and most other parameters in the model can be altered by the user to adapt the model to a given situation.)

Seven different enterprise options are represented in the standard RIM model. These are wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), lupins (*Lupinus angustifolius*), self-regenerating subterranean clover (*Trifolium subterraneum* L.), French serradella, and a volunteer pasture consisting mainly of grasses, herbs, and some legumes. The model is extended in this study to incorporate lucerne pasture. The user selects the rotation to plant over the twenty-year horizon and then is able to compare the profitability of alternative IWM strategies (combinations of weed treatments). It is assumed here that the producer wishes to maximise the profitability of the field over the twenty-year planning horizon.

Monetary values are discounted to a present value at the beginning of the planning horizon. The present value of income (*I*) earned in year *t* is $I_t \times (1+r)^{-t}$, where *r* represents a discount rate. The economic rationale behind discounting is that \$*I* invested over *t* years at rate *r* will yield $\$I(1+r)^t$ after *t* years, so income earned earlier in the horizon is more valuable than that received later. The profitability of each rotation is therefore represented in terms of net present value (NPV), where $NPV = \sum_{t=1}^{20}(1+r)^{-t} I_t$.

Crop yield is enhanced if a crop or pasture is killed with herbicide ("brown-manured") or ploughed in while still green ("green-manured") in the preceding year to obtain highly-effective weed control. In addition, yield increases if pasture or crop legumes are included in the rotation in the preceding two years. In contrast, yield is depressed by late-sowing, if barley or canola is not swathed, or because of phytotoxic damage from selective-herbicide application. Crop yield (ϑ^L) is also reduced through competition with annual ryegrass. This is defined in the relationship (Cousens, 1985),

$$\vartheta^L(w_t) = (1-z) + z\left(\frac{(1+a^L)}{d_s}\right)\left(\frac{d_o}{a^L + d_o + kw_t}\right), \tag{1}$$

where w_t is the weed population present at harvest, *z* is the maximum proportion of grain yield lost at high weed density, a^L is the background competition factor for land use *L*, d_s is the standard crop density, d_o is the observed crop density, and *k* is a constant representing the degree of competition between the weed population and the grain crop. General costs include those for broadleaf weed control, crop insurance, cultivation, fertiliser, fuel, insecticide, machinery maintenance, seed, and weed treatments.

The profitability of a given year of pasture is determined by the multiplication of the standard gross margin received for sheep farming in the study area (measured in dollars per dry sheep equivalent ($ DSE^{-1})) and the relevant stocking rate (measured in DSE ha^{-1}). A DSE is a standard measure of livestock representing one non-lactating sheep of average size. Stocking intensity varies by pasture type and the age of the sward.

Simulation involves experimenting with the decision parameters in the model of a system to understand its management. This method is used in the standard RIM model (Pannell et al., 2004) to identify profitable combinations of weed control treatments. This can be challenging since the decision space is large. For example, there are around 10^{119} possible combinations of treatments in the continuous-cropping rotation studied in this paper. This problem motivates the use of compressed annealing (Ohlmann et al., 2004; Doole and Pannell, 2007) to identify the most profitable combination of weed treatments in a given rotation. Compressed annealing identifies a highly profitable solution in a large and/or complex model by randomly sampling different configurations of the decision variables (Doole, 2007a; Doole and Pannell, 2007). Unprofitable and/or infeasible solutions identified through this random walk are accepted, together with more profitable configurations, as updated estimates of the most profitable set of the decision parameters early in the search procedure, allowing escapement from local maxima. However, the probability of accepting these inferior solutions is reduced over time, therefore the algorithm focuses more effort on improving profitable solutions in the feasible region as the search proceeds.

This implementation of the compressed annealing algorithm converges to different near-optimal solutions, even from the same initial configuration, because the large size of the model prevents the identification of a global maximum (i.e., the single set of the decision parameters that maximises profit for a given rotation) and the procedure is probabilistic. Accordingly, the result reported for each problem instance is the most profitable configuration identified from ten runs of the algorithm.

A terminal condition is introduced to reduce the probability that the system will be mismanaged towards the end of the horizon under the optimal strategy. The terminal seed population must be under the initial seed population if this initial seed burden is below 500 seeds m^{-2}. And, the terminal seed population must be below 500 seeds m^{-2} if the initial seed population is above 500 seeds m^{-2}. A seed population of 500 seeds m^{-2} is an estimate of the average number of seeds present in the soil in central wheatbelt farming systems (Pannell et al., 2004).

2.2 Weed control options

The version of RIM used includes 50 weed treatment options, including a broad range of selective herbicides, non-selective herbicides and cultural methods considered relevant to the study region. The model does not permit incompatible configurations of treatments; for example, a wheat crop cannot be grazed.

Apart from standard herbicide options, a feature of the model is its representation of a wide range of non-chemical control methods. Of these, most of the following will feature in results presented later:

1. *Knockdown herbicide application*: The application of a non-selective herbicide prior to crop emergence can reduce early weed competition.
2. *High intensity grazing*: Grazing a field at high stocking rates so that sheep graze the seed heads of flowering weeds can reduce seed production.
3. *Winter-cleaning*: Non-selective herbicide can be applied during winter to reduce annual ryegrass populations prior to seed production.
4. *Swathing*: Cutting a crop prior to maturity can encourage consistent drying of the crop and simultaneously cut weed seed heads prior to seed production.
5. *Seed catching*: Weed seeds can be collected at harvest to prevent their return to the soil.
6. *Windrowing*: Harvest residue can be collected in rows for subsequent burning.
7. *Brown-manuring*: A pasture or crop may be killed with a non-selective herbicide to prevent annual ryegrass plants setting seed.
8. *Green-manuring*: A pasture or crop that is actively growing may be ploughed into the soil to prevent weed seed production.
9. *Hay/silage production*: A pasture or crop may be cut for hay or silage to prevent annual ryegrass plants from setting seed.

2.3 Extension of RIM to include lucerne

Much of the following information is taken from unpublished work provided by the Department of Agriculture and Food Western Australia (DAFWA) and relevant extension publications (e.g., Devenish, 2001; Latta et al., 2003). Some parameter estimates are based on the expert opions of experienced scientists and agronomists, where insufficient firm field data is available.

It is assumed that lucerne is sown fifty days after the break of season to obtain good weed control prior to emergence (Devenish, 2001). In this region, lucerne may be sown with (1) an autumn "tickle" (shallow cultivation) to promote weed germination and separate applications of two knockdown herbicides (paraquat/diquat and glyphosate) prior to sowing, or (2) an autumn tickle and incorporation of trifluralin into the soil at seeding (Devenish, 2001; Latta et al., 2003). Each of these methods is assumed to kill 80 per cent of annual ryegrass plants (DAFWA, unpublished data). The cost of lucerne establishment (not incorporating weed management costs) is A$88.30 (Doole, 2007b). The stocking rate for the lucerne pasture is 1.1 DSE ha^{-1} yr^{-1} in the first year and 7 DSE ha^{-1} yr^{-1} in the second and third years of the pasture (DAFWA, unpublished data). Only three-year lucerne phases are studied in this paper since (1) lucerne persistence beyond three years is harmed by disease and drought in the study region, and (2) the high profitability of cropping motivates farmers against a longer pasture phase.

No ryegrass control is achieved by grazing in the first year of a lucerne phase since the stocking rate is very low. In the second and third years, grazing pressure is sufficiently high to reduce seed set substantially, at rates assumed to be equivalent to those for subterranean clover under intensive grazing (e.g., 92 and 95 per cent reduction in the second and third years of pasture, respectively) (Pannell et al., 2004). This provides a conservative estimate of the level of weed control as lucerne is more competitive with weeds than annual pasture (Lyons and Latta, 2003).

Nitrogen fixation by lucerne is valued using the method of Pannell and Falconer (1988). These authors recognise interdependence between biologically fixed and fertiliser nitrogen; thus, they quantify (a) the reduction in the amount of nitrogenous fertiliser required following N fixation by legumes, and (b) the increase in the yield of cereal crops that follow the legume in rotation (independent of N fertiliser rate). Lucerne increases cereal crop yield by 40 per cent (cf. 30 per cent) in the first (cf. second) crop that follows this pasture (DAFWA, unpublished data). In addition, 30 kg N ha^{-1} (cf. 10 kg N ha^{-1}) is saved in the first (cf. second) cereal crop (DAFWA, unpublished data). These values are similar to those identified in field trials conducted throughout the Western Australian wheatbelt (e.g., Latta et al., 2001).

A winter-cleaning option, involving the application of Spray.Seed® herbicide, is also incorporated in the model. Spray.Seed® is applied at 1.5 L ha^{-1} (0.2025 kg a.i. ha^{-1} paraquat and 0.1725 kg a.i. ha^{-1} diquat) and is assumed to kill 95 per cent of annual ryegrass plants (DAFWA, unpublished data).

Effective removal of lucerne is necessary to reduce competition in the subsequent cropping phase. Lucerne is removed in spring with a mixture of 1 litre of glyphosate (0.4 kg a.i. ha^{-1}) and 1.5 litres of 2,4-D Amine (0.9375 kg a. i. ha^{-1}) per hectare (Latta et al., 2003). It is assumed that this treatment also kills 98 per cent of adult annual ryegrass plants (DAFWA, unpublished data). Herbicide costs are A\$5 L^{-1} for glyphosate and A\$7.59 L^{-1} for 2,4-D Amine (Agriculture Western Australia, 2004). The application cost is A\$2.50. Thus, the total cost to remove lucerne is A\$18.90.

2.4 Rotations

The value of perennial pasture for weed control in the study region is determined through the evaluation of seven rotations (Table 2). These are based on typical sequences in the study region and on the results of previous research (e.g., Monjardino et al., 2004). Each rotation is represented using a short label for ease of reference.

The continuous cropping rotation is representative of farming systems in which very high pressure is placed on the herbicide resource through limiting the diversity of permissible weed management strategies. Similar to lucerne, serradella supports grazing, fixes nitrogen from the atmosphere, and permits high weed kill through brown-manuring (Doole and Pannell, 2007). However, its establishment cost is lower than that for lucerne, at around A\$34 ha^{-1}. This arises mainly due to the lower cost of seed, which may be harvested on-farm using a standard harvester. It therefore provides an interesting pasture enterprise to which lucerne can be compared.

[Insert Table 1 here]

Practices implemented at seeding for all pastures and crops and the removal of lucerne are all selected exogenously in the model. This allows the employment of sowing patterns generally adopted in the study region and allows for simpler coding of the search algorithm because many of the enterprises represented in the RIM model require different seeding practices. For example, in relation to the latter, serradella and lucerne are both sown at the beginning of a phase, but their timing of seeding relative to the primary crops differs markedly, with lucerne typically being sown up to a month later than serradella.

3. Results and discussion

This section presents the results of the model and discusses their implications for farms in the study region. The profitability of each rotation is presented for a range of initial ryegrass seed densities (Table 2), a range of livestock profitability levels (Table 4), and various degrees of initial herbicide resistance (Table 5). The standard assumptions are initial seed density 500 seeds m^{-2}; sheep gross margin A\$15 DSE^{-1}; and no initial herbicide resistance. In the simulations, resistance develops over time as the available stock of herbicide applications for each herbicide group is exhausted. Profitability is represented as a difference relative to a baseline determined by the net present value (in A$ ha^{-1}) of the continuous-cropping rotation.

3.1 Initial weed-seed density

Given no initial herbicide resistance and base-case livestock profitability (Table 2), the continuous-cropping rotation is the most-profitable sequence at low to moderate initial weed densities. In this situation, selective herbicide applications are sufficiently effective at containing weed competition. However, the relative profitability of including a pasture phase generally increases as the initial seed burden increases (Table 2).[1] The *S+7C* rotation is the most profitable sequence of those simulated in this study at initial seed densities above 1000 seeds m^{-2} as the pasture phase provides effective, regular weed control (particularly through brown-manuring and grazing) without displacing many years of crop.

[Insert Table 2 near here]

Serradella is more profitable than lucerne pasture in these initial results for two reasons: (a) the economic returns from cropping in the absence of initial herbicide resistance means that a three-year lucerne phase involves a higher income sacrifice or "opportunity cost" than a single year of serradella; and (b) lucerne has a higher establishment cost. Of the two lucerne rotation options, the *3L+7C* system is much more valuable than the *3L+3C* rotation in these results, given the latter system's significant displacement of crop.

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[1] The results presented in Table 2 display significant variability given that the search algorithm is probabilitistic and is unable to identify the single configuration of the decision variables that maximises profit in this model due to its enormous size.

Table 3 lists the integrated weed management strategies identified by the search algorithm in the first three runs performed for the *3L+7C* rotation. The employment of knockdown herbicide applications, high-intensity grazing, applications of non-selective herbicides for pasture topping in the lucerne phase, and harvest treatments (i.e., seed catching and windrowing) is remarkably uniform across the three strategies (Table 3), and also in the remaining runs (data not shown). This identifies a set of critical weed management techniques that may be used within a profitable IWM strategy in a lucerne-crop rotation. Also, it demonstrates the high potential value of using a search algorithm to identify profitable IWM strategies in a complex simulation model (Doole and Pannell, 2007). However, though these three runs are very similar in value, there is a wide diversity in the timing and type of selective herbicide application (Table 3). In particular, the third run identifies that the adoption of a regular lucerne phase and consistent use of knockdown herbicide applications and post-harvest treatments in cereal crops can achieve profitable levels of weed control, even relative to those that may be achieved with much higher chemical use. Also, this diversity is valuable as producers may conceptually select the IWM strategy most suitable for their personal situation with some knowledge of its profitability relative to alternative approaches.

[Insert Table 3 near here]

3.2 Livestock profitability

Increases in livestock profitability can greatly promote the attractiveness of pasture phases, including lucerne. If the sheep gross margin is A$22.50 or higher, *3L+7C* becomes the most profitable rotation option, even without the initial presence of herbicide resistance. However, this is higher than the A$21.50 DSE^{-1} estimate computed by Agriculture Western Australia for 2002, a year of particularly strong sheep meat prices. Such substantial increases are considered unlikely to be sustained in the long term given forecast reductions in the global demand for wool (Sackett, 2004) and low rates of productivity growth in existing Australian sheep flocks (Banks, 2005). Nevertheless, relatively high livestock profitability, combined with the other factors identified in this analysis, should encourage the use of either of the pasture types studied here.

[Insert Table 4 near here]

3.3 Herbicide resistance

Table 5 presents output for situations with different levels of initial herbicide resistance. Costly non-selective treatments become necessary for weed control in the continuous-cropping rotation as resistance increasingly constrains production. (This includes the cutting of wheat for hay and the cutting of lupins for silage.) It is more profitable to employ these costly non-selective treatments than use no control and experience large yield losses due to the competitiveness of annual ryegrass (Lemerle et al., 1995). Consequently, most of those rotations containing serradella are similarly profitable to the continuous-cropping rotation if annual ryegrass is resistant to Group A herbicides at the beginning of the planning horizon. Moreover, nearly all sequences incorporating pasture are more profitable than the continuous-cropping rotation if ryegrass is initially resistant to Group A and Group B herbicides.

[Insert Table 5 near here]

These findings highlight the importance of pasture for the management of resistant weeds given the extensive development of resistance to Group A and B herbicides in this area. For example, around 70 per cent of ryegrass populations in the Western

Australian wheatbelt have been found to contain plants resistant to Group A chemicals, with 90 per cent showing resistance to Group B (Owen et al., 2007). The modelling result that pasture phases provide better opportunities for control of resistant weeds than do lupin crops is consistent with current trends in the region, where increasing substitution of pasture phases for lupin crops is being observed.

The most-valuable sequences when ryegrass is resistant to at least Group A and B herbicides in Year 1 are those containing a high proportion of pasture. The *3S+7C* rotation is the most-profitable sequence when annual ryegrass is initially resistant to Group A–B and Group A–C chemicals, but the *3L+7C* sequence is more valuable when no selectives are available in the initial year. These findings reflect the high degree of weed control that may be attained in an extended pasture phase, even in the absence of selective herbicides. Lucerne is most profitable when no selectives are available as high levels of weed control can be obtained through grazing, winter-cleaning, spray-topping, and the removal of lucerne with non-selective herbicides (Lyons and Latta, 2003). This is also demontrated in the profitability of Run 3 in Table 3 (which employs a very low number of selective herbicides) relative to the other results described therein. This evidence suggests that extended pasture phases will become increasingly economically attractive in the study region since Group C and Group D resistance is growing throughout the wheatbelt (Owen et al., 2007)

Figure 1 presents the annual ryegrass seed population at the beginning at the growing season for two rotations at two different levels of reistance severity. Here, “full resistance” denotes the inefficacy of all selective herbicides against this weed. (The last year of the twenty-year planning horizon is truncated in Figure 1 as it is influenced, albeit slightly, by the terminal condition of the model.) The incorporation of a frequent lucerne phase allows effective control of the ryegrass population, whether selective herbicides are effective or not against this weed. However, the non-selective treatments required in the *C* rotation in the full resistance state are less efficient than selective herbicides. Therefore, in addition to this strategy being more costly to implement, it is also less able to adequately reduce the number of seeding plants, and therefore successfully diminish the seed population, early in the planning horizon (Figure 1). The germination of these seeds consequently reduces yield, and hence profit, in subsequent crops if these germinated seeds successfully reach adulthood. In contrast, the availability of effective selective herbicides allows economic control of the weed burden in the *C* sequence.

[Insert Figure 1 near here]

4. Conclusion

The RIM framework is extended in this research to incorporate weed management strategies available in a lucerne pasture phase in a crop-pasture rotation in the Western Australian wheatbelt. Lucerne has a complex mixture of advantages (e.g., improved weed management, nitrogen fixation, and high grazing value once well established) and disadvantages (e.g., high establishment costs and poor productivity in its first year) for this mixed farming system. Therefore a detailed and systematic analysis is required to assess its overall economic performance relative to other land use options.

Rotations that include lucerne were compared with a rotation involving continuous cropping, and rotations that have a mixture of crops and annual pastures, particularly serradella pasture.

Under our base-cases assumptions, continuous cropping was the most profitable option over a twenty-year planning horizon, even allowing for the fact that it led to the relatively rapid onset of herbicide resistance, and allowed a relatively limited range of weed control options.

If weed seed density is relatively high, or livestock production is relatively profitable, or herbicide resistance is already present in the field, then rotations that include pasture become more attractive. Lucerne becomes the best pasture option when herbicide resistance is more severe, and/or livestock production is most profitable. In less extreme circumstances, the annual pasture serradella is preferred. Given the growing prevalence of herbicide resistance in this region, we expect to see an increasing role for lucerne pasture, at least in cases where farmers have suffered the loss of all selective herbicides. Furthermore, the value of lucerne for salinity containment has not been considered here and is expected to augment its relative profitability. This is an important area for further research.

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Table 1. Candidate rotations and associated labels.

Rotation	**Label**
lupin-wheat-wheat-barley	*C*
serradella-wheat-wheat-barley	*S+3C*
lucerne-lucerne-lucerne-wheat-wheat-barley	*3L+3C*
serradella-wheat-wheat-barley-lupin-wheat-wheat-barley	*S+7C*
serradella-serradella-wheat-wheat-barley-lupin-wheat-wheat-barley	*2S+7C*
serradella-serradella-serradella-wheat-wheat-barley-lupin-wheat-wheat-barley	*3S+7C*
lucerne-lucerne-lucerne-wheat-wheat-barley-lupin-wheat-wheat-barley	*3L+7C*

Table 2. Value (NPV in A$ ha^{-1}) of each rotation containing pasture relative to continuous cropping over a range of initial seed densities. (Sheep gross margin A$15 DSE^{-1}; no initial herbicide resistance)

Rotation	**Initial ryegrass seed density (seeds m^{-2})**						
	100	**250**	**500**	**1,000**	**2,500**	**5,000**	**10,000**
S+7C	-8	-7	-14	-13	+11	+3	+24
S+3C	-20	-34	-36	-35	-23	-17	+6
3S+7C	-22	-32	-34	-27	-3	-2	+22
2S+7C	-69	-68	-60	-68	-56	-38	-27
3L+7C	-87	-95	-87	-78	-61	-59	-38
3L+3C	-244	-254	-242	-240	-221	-219	-195

Table 3. Optimal integrated weed management strategies identified by compressed annealing in the first three runs performed for the *3L+7C* sequence.

Run 1 (NPV=A$605)	**Run 2 (NPV=A$602)**	**Run 3 (NPV=A$608)**
10 knockdown herbicide applications	11 knockdown herbicide applications	10 knockdown herbicide applications
1 application of Fusilade® (Group A fop)	1 application of Fusilade®	2 applications of Fusilade®
2 applications of Select® (Group A dim)	1 application of Select®	1 application of simazine
2 applications of Glean® (Group B)	1 application of simazine	-
1 application of simazine (Group C)	1 application of trifluralin (Group D)	-
6 instances of high intensity grazing	6 instances of high intensity grazing	6 instances of high intensity grazing
1 winter-cleaning of lucerne with Spray.Seed	-	-
2 pasture-topping applications with glyphosate and 1 with Gramoxone®	2 pasture-topping applications with glyphosate and 1 with Gramoxone®	2 pasture-topping applications with glyphosate and 1 with Gramoxone®
Swathe lupins twice	Swathe lupins three times	Swathe lupins once
Use seed catching 6 times and windrowing 4 times	Use seed catching 4 times and windrowing 9 times	Use seed catching 10 times and windrowing once

Figure 1. Number of annual ryegrass seeds present in the soil at the beginning of the growing season in two rotations at two different states of herbicide resistance. (Initial seed density 500 seeds m^{-2})

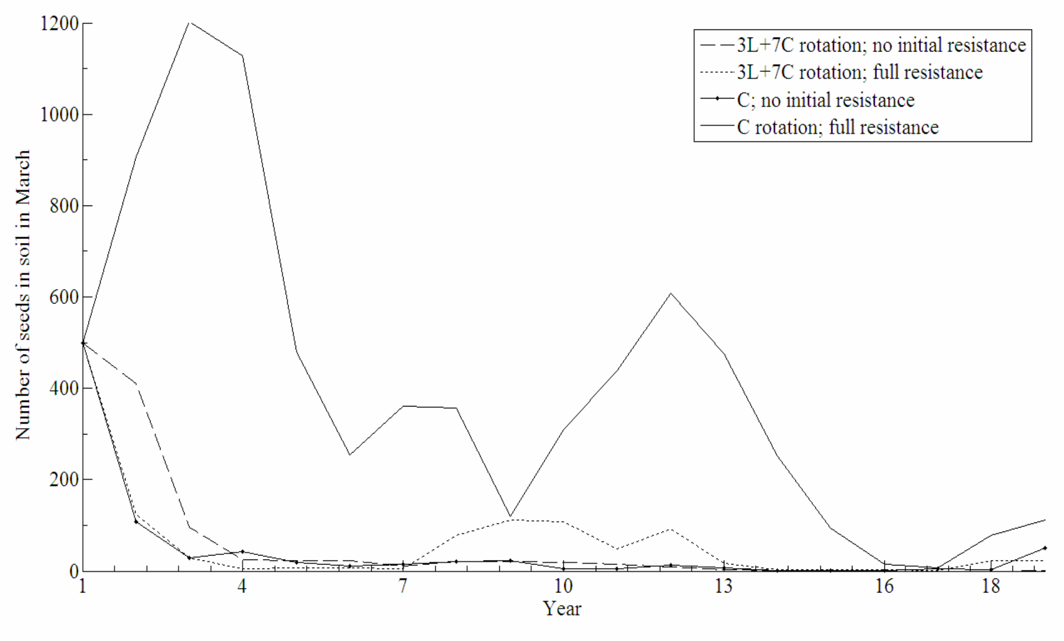

Table 4. Value (NPV in A$ ha^{-1}) of each rotation relative to continuous cropping for a range of sheep gross margins. (Initial seed density 500 seeds m^{-2}; no initial herbicide resistance)

Rotation	**Sheep gross margin (A$ DSE^{-1})**						
	10	**12.50**	**15**[a]	**17.50**	**20**	**22.50**	**25**
S+7C	-27	-24	-14	-12	+7	+17	+38
S+3C	-78	-53	-36	-24	+14	+25	+52
3S+7C	-125	-66	-34	-26	+21	+41	+69
2S+7C	-104	-101	-60	-58	-23	-21	+22
3L+7C	-169	-124	-87	-70	-44	+43	+75
3L+3C	-353	-311	-242	-173	-119	-57	+6

[a] Base case.

Table 5. Value (NPV in A\$ ha^{-1}) of each rotation relative to continuous cropping for alternative herbicide-resistance scenarios. (Initial seed density 500 seeds m^{-2}; sheep gross margin A\$15 DSE^{-1})

Rotation	**Herbicide groups to which annual ryegrass is resistant in Year 1**				
	None	**A**	**A, B**	**A, B, C**	**A, B, C, D**
S+7C	-14	-5	+28	+98	+178
S+3C	-36	+3	+38	+111	+222
3S+7C	-34	-7	+41	+128	+210
2S+7C	-60	-50	+3	+72	+242
3L+7C	-87	-56	+5	+120	+340
3L+3C	-242	-207	-141	+51	+166