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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1 **Abstract.** Use of lucerne (*Medicago sativa* L.) pastures in crop rotations has been

2 proposed as a method to enhance weed management options for growers facing

3 herbicide resistance in Western Australia. An existing model for analysing herbicide

4 resistance in the important crop weed annual ryegrass (*Lolium rigidum* Gaud.) is

5 consequently extended to include lucerne, used for grazing by a sheep enterprise. Seven

6 rotational options are analysed, including various combinations of lucerne, annual

7 pastures, and crops. Lucerne provides additional weed management benefits across the

8 rotation, but in the region studied these benefits are only sufficient to make lucerne

9 rotations the most profitable option in situations where ryegrass is resistant to multiple

10 herbicide groups, and/or livestock prices are very high.

11 **Key words.** Herbicide resistance, integrated weed management, economics, weed

12 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.

40   *Cadiz*), for the control of herbicide-resistant weeds in Western Australian farming

41   systems (Doole and Pannell, 2007).

42   The research problem addressed here is complex, involving the (a) dynamics of weed

43   populations, (b) dynamics of herbicide-resistance development, (c) alternative crop and

44   pasture options in many possible sequences, (d) competitive effects of weeds, (e)

45   phytotoxic effects of treatments, (f) many possible weed management strategies, and (g)

46   economic consequences. The complexity makes it difficult for farmers to assess

47   alternative strategies through trialling, and this may inhibit the adoption of new

48   practices (Pannell et al., 2006). Field experiments have a limited role in the

49   development of robust management strategies, since there are too many possible

50   strategies to physically trial. For these reasons, the study is based on bioeconomic

51   modelling, integrating experimental and other information into a systems analysis. This

52   multidisciplinary approach is important given the economic implications of on-farm

53   weed management, but its intrinsic links to agronomic, biological, and chemical

54   processes.

55   Section 2 includes descriptions of the model, the weed control options and the

56   alternative rotations used to determine the relative profitability of sequences containing

57   lucerne pasture. The results of the analysis are presented and discussed in Section 3.

58   Key findings are summarised in Section 4.

59   **2. Model**

60   *2.1 Model description*

61   This application employs the resistance and integrated management (RIM) model to

62   investigate the profitability of alternative IWM strategies to control herbicide-resistant

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63 annual ryegrass on a single field in the central wheatbelt of Western Australia (Pannell

64 et al., 2004). This description of the model is based on typical explanations of the RIM

65 model in the existing literature (e.g., Pannell et al., 2004; Doole and Pannell, 2007). The

66 RIM framework is a deterministic simulation model representing the multiple-cohort

67 dynamics of ryegrass plants and seeds, their interactions with crops and pastures, and

68 the effects of a broad range of weed control strategies (see Section 2.2). The model

69 allows the simulation of management strategies over a twenty-year period to capture the

70 dynamic nature of weed populations and resistance development.

71 The representation of the onset of herbicide resistance is simple but realistic (Pannell et

72 al., 2004). Each herbicide mode-of-action can only be used a limited number of times in

73 the model before resistance occurs. For this application, the assumed numbers of

74 applications of each selective herbicide group available before resistance develops are

75 as follows: 2 doses of each type of ACCase inhibitor herbicides ("fops" and "dims", or

76 Group A in the Herbicide Resistance Action Committee system (Kramer and Schirmer,

77 2007)), 2 doses of sulfonylurea herbicides (e.g., chlorulfuron, Group B), 5 doses of

78 photosynthesis inhibitor herbicides (e.g., simazine, Group C), and 5 doses of

79 dinitroanaline herbicides (e.g., trifluralin, Group D). (However, these assumptions and

80 most other parameters in the model can be altered by the user to adapt the model to a

81 given situation.)

82 Seven different enterprise options are represented in the standard RIM model. These are

83 wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.),

84 lupins (*Lupinus angustifolius*), self-regenerating subterranean clover (*Trifolium*

85 *subterraneum* L.), French serradella, and a volunteer pasture consisting mainly of

86 grasses, herbs, and some legumes. The model is extended in this study to incorporate

87   lucerne pasture. The user selects the rotation to plant over the twenty-year horizon and

88   then is able to compare the profitability of alternative IWM strategies (combinations of

89   weed treatments). It is assumed here that the producer wishes to maximise the

90   profitability of the field over the twenty-year planning horizon.

91   Monetary values are discounted to a present value at the beginning of the planning

92   horizon. The present value of income (I) earned in year t is $I_t \times (1+r)^{-t}$, where r

93   represents a discount rate. The economic rationale behind discounting is that \$$I$ invested

94   over t years at rate r will yield \$$I(1+r)^t$ after t years, so income earned earlier in the

95   horizon is more valuable than that received later. The profitability of each rotation is

96   therefore represented in terms of net present value (NPV), where $NPV = \sum\limits_{t=1}^{20}(1+r)^{-t}I_t$.

97   Crop yield is enhanced if a crop or pasture is killed with herbicide ("brown-manured")

98   or ploughed in while still green ("green-manured") in the preceding year to obtain

99   highly-effective weed control. In addition, yield increases if pasture or crop legumes are

100   included in the rotation in the preceding two years. In contrast, yield is depressed by

101   late-sowing, if barley or canola is not swathed, or because of phytotoxic damage from

102   selective-herbicide application. Crop yield (ϑ^L) is also reduced through competition

103   with annual ryegrass. This is defined in the relationship (Cousens, 1985),

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

105   where w_t is the weed population present at harvest, z is the maximum proportion of

106   grain yield lost at high weed density, a^L is the background competition factor for land

107   use L, d_s is the standard crop density, d_o is the observed crop density, and k is a

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108   constant representing the degree of competition between the weed population and the

109   grain crop. General costs include those for broadleaf weed control, crop insurance,

110   cultivation, fertiliser, fuel, insecticide, machinery maintenance, seed, and weed

111   treatments.

112   The profitability of a given year of pasture is determined by the multiplication of the

113   standard gross margin received for sheep farming in the study area (measured in dollars

114   per dry sheep equivalent ($ DSE^{-1})) and the relevant stocking rate (measured in DSE

115   ha^{-1}). A DSE is a standard measure of livestock representing one non-lactating sheep of

116   average size. Stocking intensity varies by pasture type and the age of the sward.

117   Simulation involves experimenting with the decision parameters in the model of a

118   system to understand its management. This method is used in the standard RIM model

119   (Pannell et al., 2004) to identify profitable combinations of weed control treatments.

120   This can be challenging since the decision space is large. For example, there are around

121   10^{119} possible combinations of treatments in the continuous-cropping rotation studied in

122   this paper. This problem motivates the use of compressed annealing (Ohlmann et al.,

123   2004; Doole and Pannell, 2007) to identify the most profitable combination of weed

124   treatments in a given rotation. Compressed annealing identifies a highly profitable

125   solution in a large and/or complex model by randomly sampling different configurations

126   of the decision variables (Doole, 2007a; Doole and Pannell, 2007). Unprofitable and/or

127   infeasible solutions identified through this random walk are accepted, together with

128   more profitable configurations, as updated estimates of the most profitable set of the

129   decision parameters early in the search procedure, allowing escapement from local

130   maxima. However, the probability of accepting these inferior solutions is reduced over

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131 time, therefore the algorithm focuses more effort on improving profitable solutions in

132 the feasible region as the search proceeds.

133 This implementation of the compressed annealing algorithm converges to different near-

134 optimal solutions, even from the same initial configuration, because the large size of the

135 model prevents the identification of a global maximum (i.e., the single set of the

136 decision parameters that maximises profit for a given rotation) and the procedure is

137 probabilistic. Accordingly, the result reported for each problem instance is the most

138 profitable configuration identified from ten runs of the algorithm.

139 A terminal condition is introduced to reduce the probability that the system will be

140 mismanaged towards the end of the horizon under the optimal strategy. The terminal

141 seed population must be under the initial seed population if this initial seed burden is

142 below 500 seeds m^{-2}. And, the terminal seed population must be below 500 seeds m^{-2} if

143 the initial seed population is above 500 seeds m^{-2}. A seed population of 500 seeds m^{-2} is

144 an estimate of the average number of seeds present in the soil in central wheatbelt

145 farming systems (Pannell et al., 2004).

146 *2.2 Weed control options*

147 The version of RIM used includes 50 weed treatment options, including a broad range

148 of selective herbicides, non-selective herbicides and cultural methods considered

149 relevant to the study region. The model does not permit incompatible configurations of

150 treatments; for example, a wheat crop cannot be grazed.

151 Apart from standard herbicide options, a feature of the model is its representation of a

152 wide range of non-chemical control methods. Of these, most of the following will

153 feature in results presented later:

154   1. *Knockdown herbicide application*: The application of a non-selective herbicide

155   prior to crop emergence can reduce early weed competition.

156   2. *High intensity grazing*: Grazing a field at high stocking rates so that sheep graze

157   the seed heads of flowering weeds can reduce seed production.

158   3. *Winter-cleaning*: Non-selective herbicide can be applied during winter to reduce

159   annual ryegrass populations prior to seed production.

160   4. *Swathing*: Cutting a crop prior to maturity can encourage consistent drying of

161   the crop and simultaneously cut weed seed heads prior to seed production.

162   5. *Seed catching*: Weed seeds can be collected at harvest to prevent their return to

163   the soil.

164   6. *Windrowing*: Harvest residue can be collected in rows for subsequent burning.

165   7. *Brown-manuring*: A pasture or crop may be killed with a non-selective herbicide

166   to prevent annual ryegrass plants setting seed.

167   8. *Green-manuring*: A pasture or crop that is actively growing may be ploughed

168   into the soil to prevent weed seed production.

169   9. *Hay/silage production*: A pasture or crop may be cut for hay or silage to prevent

170   annual ryegrass plants from setting seed.

171   *2.3 Extension of RIM to include lucerne*

172   Much of the following information is taken from unpublished work provided by the

173   Department of Agriculture and Food Western Australia (DAFWA) and relevant

174   extension publications (e.g., Devenish, 2001; Latta et al., 2003). Some parameter

175   estimates are based on the expert opions of experienced scientists and agronomists,

176   where insufficient firm field data is available.

177 It is assumed that lucerne is sown fifty days after the break of season to obtain good

178 weed control prior to emergence (Devenish, 2001). In this region, lucerne may be sown

179 with (1) an autumn "tickle" (shallow cultivation) to promote weed germination and

180 separate applications of two knockdown herbicides (paraquat/diquat and glyphosate)

181 prior to sowing, or (2) an autumn tickle and incorporation of trifluralin into the soil at

182 seeding (Devenish, 2001; Latta et al., 2003). Each of these methods is assumed to kill

183 80 per cent of annual ryegrass plants (DAFWA, unpublished data). The cost of lucerne

184 establishment (not incorporating weed management costs) is A\$88.30 (Doole, 2007b).

185 The stocking rate for the lucerne pasture is 1.1 DSE ha^{-1} yr^{-1} in the first year and 7 DSE

186 ha^{-1} yr^{-1} in the second and third years of the pasture (DAFWA, unpublished data). Only

187 three-year lucerne phases are studied in this paper since (1) lucerne persistence beyond

188 three years is harmed by disease and drought in the study region, and (2) the high

189 profitability of cropping motivates farmers against a longer pasture phase.

190 No ryegrass control is achieved by grazing in the first year of a lucerne phase since the

191 stocking rate is very low. In the second and third years, grazing pressure is sufficiently

192 high to reduce seed set substantially, at rates assumed to be equivalent to those for

193 subterranean clover under intensive grazing (e.g., 92 and 95 per cent reduction in the

194 second and third years of pasture, respectively) (Pannell et al., 2004). This provides a

195 conservative estimate of the level of weed control as lucerne is more competitive with

196 weeds than annual pasture (Lyons and Latta, 2003).

197 Nitrogen fixation by lucerne is valued using the method of Pannell and Falconer (1988).

198 These authors recognise interdependence between biologically fixed and fertiliser

199 nitrogen; thus, they quantify (a) the reduction in the amount of nitrogenous fertiliser

200 required following N fixation by legumes, and (b) the increase in the yield of cereal

201   crops that follow the legume in rotation (independent of N fertiliser rate). Lucerne

202   increases cereal crop yield by 40 per cent (cf. 30 per cent) in the first (cf. second) crop

203   that follows this pasture (DAFWA, unpublished data). In addition, 30 kg N ha^{-1} (cf. 10

204   kg N ha^{-1}) is saved in the first (cf. second) cereal crop (DAFWA, unpublished data).

205   These values are similar to those identified in field trials conducted throughout the

206   Western Australian wheatbelt (e.g., Latta et al., 2001).

207   A winter-cleaning option, involving the application of Spray.Seed® herbicide, is also

208   incorporated in the model. Spray.Seed® is applied at 1.5 L ha^{-1} (0.2025 kg a.i. ha^{-1}

209   paraquat and 0.1725 kg a.i. ha^{-1} diquat) and is assumed to kill 95 per cent of annual

210   ryegrass plants (DAFWA, unpublished data).

211   Effective removal of lucerne is necessary to reduce competition in the subsequent

212   cropping phase. Lucerne is removed in spring with a mixture of 1 litre of glyphosate

213   (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

214   al., 2003). It is assumed that this treatment also kills 98 per cent of adult annual ryegrass

215   plants (DAFWA, unpublished data). Herbicide costs are A$5 L^{-1} for glyphosate and

216   A$7.59 L^{-1} for 2,4-D Amine (Agriculture Western Australia, 2004). The application

217   cost is A$2.50. Thus, the total cost to remove lucerne is A$18.90.

218   *2.4 Rotations*

219   The value of perennial pasture for weed control in the study region is determined

220   through the evaluation of seven rotations (Table 2). These are based on typical

221   sequences in the study region and on the results of previous research (e.g., Monjardino

222   et al., 2004). Each rotation is represented using a short label for ease of reference.

223 The continuous cropping rotation is representative of farming systems in which very

224 high pressure is placed on the herbicide resource through limiting the diversity of

225 permissible weed management strategies. Similar to lucerne, serradella supports

226 grazing, fixes nitrogen from the atmosphere, and permits high weed kill through brown-

227 manuring (Doole and Pannell, 2007). However, its establishment cost is lower than that

228 for lucerne, at around A\$34 ha^{-1}. This arises mainly due to the lower cost of seed, which

229 may be harvested on-farm using a standard harvester. It therefore provides an

230 interesting pasture enterprise to which lucerne can be compared.

231 [Insert Table 1 here]

232 Practices implemented at seeding for all pastures and crops and the removal of lucerne

233 are all selected exogenously in the model. This allows the employment of sowing

234 patterns generally adopted in the study region and allows for simpler coding of the

235 search algorithm because many of the enterprises represented in the RIM model require

236 different seeding practices. For example, in relation to the latter, serradella and lucerne

237 are both sown at the beginning of a phase, but their timing of seeding relative to the

238 primary crops differs markedly, with lucerne typically being sown up to a month later

239 than serradella.

240 **3. Results and discussion**

241 This section presents the results of the model and discusses their implications for farms

242 in the study region. The profitability of each rotation is presented for a range of initial

243 ryegrass seed densities (Table 2), a range of livestock profitability levels (Table 4), and

244 various degrees of initial herbicide resistance (Table 5). The standard assumptions are

245 initial seed density 500 seeds m^{-2}; sheep gross margin A\$15 DSE^{-1}; and no initial

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246 herbicide resistance. In the simulations, resistance develops over time as the available

247 stock of herbicide applications for each herbicide group is exhausted. Profitability is

248 represented as a difference relative to a baseline determined by the net present value (in

249 A$ ha^{-1}) of the continuous-cropping rotation.

250 *3.1 Initial weed-seed density*

251 Given no initial herbicide resistance and base-case livestock profitability (Table 2), the

252 continuous-cropping rotation is the most-profitable sequence at low to moderate initial

253 weed densities. In this situation, selective herbicide applications are sufficiently

254 effective at containing weed competition. However, the relative profitability of

255 including a pasture phase generally increases as the initial seed burden increases (Table

256 2).[1] The *S+7C* rotation is the most profitable sequence of those simulated in this study

257 at initial seed densities above 1000 seeds m^{-2} as the pasture phase provides effective,

258 regular weed control (particularly through brown-manuring and grazing) without

259 displacing many years of crop.

260 [Insert Table 2 near here]

261 Serradella is more profitable than lucerne pasture in these initial results for two reasons:

262 (a) the economic returns from cropping in the absence of initial herbicide resistance

263 means that a three-year lucerne phase involves a higher income sacrifice or "opportunity

264 cost" than a single year of serradella; and (b) lucerne has a higher establishment cost. Of

265 the two lucerne rotation options, the *3L+7C* system is much more valuable than the

266 *3L+3C* rotation in these results, given the latter system's significant displacement of

267 crop.

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

268   Table 3 lists the integrated weed management strategies identified by the search

269   algorithm in the first three runs performed for the *3L+7C* rotation. The employment of

270   knockdown herbicide applications, high-intensity grazing, applications of non-selective

271   herbicides for pasture topping in the lucerne phase, and harvest treatments (i.e., seed

272   catching and windrowing) is remarkably uniform across the three strategies (Table 3),

273   and also in the remaining runs (data not shown). This identifies a set of critical weed

274   management techniques that may be used within a profitable IWM strategy in a lucerne-

275   crop rotation. Also, it demonstrates the high potential value of using a search algorithm

276   to identify profitable IWM strategies in a complex simulation model (Doole and

277   Pannell, 2007). However, though these three runs are very similar in value, there is a

278   wide diversity in the timing and type of selective herbicide application (Table 3). In

279   particular, the third run identifies that the adoption of a regular lucerne phase and

280   consistent use of knockdown herbicide applications and post-harvest treatments in

281   cereal crops can achieve profitable levels of weed control, even relative to those that

282   may be achieved with much higher chemical use. Also, this diversity is valuable as

283   producers may conceptually select the IWM strategy most suitable for their personal

284   situation with some knowledge of its profitability relative to alternative approaches.

285   [Insert Table 3 near here]

286   *3.2 Livestock profitability*

287   Increases in livestock profitability can greatly promote the attractiveness of pasture

288   phases, including lucerne. If the sheep gross margin is A\$22.50 or higher, *3L+7C*

289   becomes the most profitable rotation option, even without the initial presence of

290   herbicide resistance. However, this is higher than the A\$21.50 DSE^{-1} estimate computed

291   by Agriculture Western Australia for 2002, a year of particularly strong sheep meat

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292 prices. Such substantial increases are considered unlikely to be sustained in the long

293 term given forecast reductions in the global demand for wool (Sackett, 2004) and low

294 rates of productivity growth in existing Australian sheep flocks (Banks, 2005).

295 Nevertheless, relatively high livestock profitability, combined with the other factors

296 identified in this analysis, should encourage the use of either of the pasture types studied

297 here.

298 [Insert Table 4 near here]

299 *3.3 Herbicide resistance*

300 Table 5 presents output for situations with different levels of initial herbicide resistance.

301 Costly non-selective treatments become necessary for weed control in the continuous-

302 cropping rotation as resistance increasingly constrains production. (This includes the

303 cutting of wheat for hay and the cutting of lupins for silage.) It is more profitable to

304 employ these costly non-selective treatments than use no control and experience large

305 yield losses due to the competitiveness of annual ryegrass (Lemerle et al., 1995).

306 Consequently, most of those rotations containing serradella are similarly profitable to

307 the continuous-cropping rotation if annual ryegrass is resistant to Group A herbicides at

308 the beginning of the planning horizon. Moreover, nearly all sequences incorporating

309 pasture are more profitable than the continuous-cropping rotation if ryegrass is initially

310 resistant to Group A and Group B herbicides.

311 [Insert Table 5 near here]

312 These findings highlight the importance of pasture for the management of resistant

313 weeds given the extensive development of resistance to Group A and B herbicides in

314 this area. For example, around 70 per cent of ryegrass populations in the Western

315 Australian wheatbelt have been found to contain plants resistant to Group A chemicals,

316 with 90 per cent showing resistance to Group B (Owen et al., 2007). The modelling

317 result that pasture phases provide better opportunities for control of resistant weeds than

318 do lupin crops is consistent with current trends in the region, where increasing

319 substitution of pasture phases for lupin crops is being observed.

320 The most-valuable sequences when ryegrass is resistant to at least Group A and B

321 herbicides in Year 1 are those containing a high proportion of pasture. The *3S+7C*

322 rotation is the most-profitable sequence when annual ryegrass is initially resistant to

323 Group A–B and Group A–C chemicals, but the *3L+7C* sequence is more valuable when

324 no selectives are available in the initial year. These findings reflect the high degree of

325 weed control that may be attained in an extended pasture phase, even in the absence of

326 selective herbicides. Lucerne is most profitable when no selectives are available as high

327 levels of weed control can be obtained through grazing, winter-cleaning, spray-topping,

328 and the removal of lucerne with non-selective herbicides (Lyons and Latta, 2003). This

329 is also demontrated in the profitability of Run 3 in Table 3 (which employs a very low

330 number of selective herbicides) relative to the other results described therein. This

331 evidence suggests that extended pasture phases will become increasingly economically

332 attractive in the study region since Group C and Group D resistance is growing

333 throughout the wheatbelt (Owen et al., 2007)

334 Figure 1 presents the annual ryegrass seed population at the beginning at the growing

335 season for two rotations at two different levels of reistance severity. Here, "full

336 resistance" denotes the inefficacy of all selective herbicides against this weed. (The last

337 year of the twenty-year planning horizon is truncated in Figure 1 as it is influenced,

338 albeit slightly, by the terminal condition of the model.) The incorporation of a frequent

339 lucerne phase allows effective control of the ryegrass population, whether selective

340 herbicides are effective or not against this weed. However, the non-selective treatments

341 required in the *C* rotation in the full resistance state are less efficient than selective

342 herbicides. Therefore, in addition to this strategy being more costly to implement, it is

343 also less able to adequately reduce the number of seeding plants, and therefore

344 successfully diminish the seed population, early in the planning horizon (Figure 1). The

345 germination of these seeds consequently reduces yield, and hence profit, in subsequent

346 crops if these germinated seeds successfully reach adulthood. In contrast, the

347 availability of effective selective herbicides allows economic control of the weed

348 burden in the *C* sequence.

349 [Insert Figure 1 near here]

350 **4. Conclusion**

351 The RIM framework is extended in this research to incorporate weed management

352 strategies available in a lucerne pasture phase in a crop-pasture rotation in the Western

353 Australian wheatbelt. Lucerne has a complex mixture of advantages (e.g., improved

354 weed management, nitrogen fixation, and high grazing value once well established) and

355 disadvantages (e.g., high establishment costs and poor productivity in its first year) for

356 this mixed farming system. Therefore a detailed and systematic analysis is required to

357 assess its overall economic performance relative to other land use options.

358 Rotations that include lucerne were compared with a rotation involving continuous

359 cropping, and rotations that have a mixture of crops and annual pastures, particularly

360 serradella pasture.

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361 Under our base-cases assumptions, continuous cropping was the most profitable option

362 over a twenty-year planning horizon, even allowing for the fact that it led to the

363 relatively rapid onset of herbicide resistance, and allowed a relatively limited range of

364 weed control options.

365 If weed seed density is relatively high, or livestock production is relatively profitable, or

366 herbicide resistance is already present in the field, then rotations that include pasture

367 become more attractive. Lucerne becomes the best pasture option when herbicide

368 resistance is more severe, and/or livestock production is most profitable. In less extreme

369 circumstances, the annual pasture serradella is preferred. Given the growing prevalence

370 of herbicide resistance in this region, we expect to see an increasing role for lucerne

371 pasture, at least in cases where farmers have suffered the loss of all selective herbicides.

372 Furthermore, the value of lucerne for salinity containment has not been considered here

373 and is expected to augment its relative profitability. This is an important area for further

374 research.

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448   predict soil water use by lucerne compared with soil water use by annual crops
449   or pastures. *Australian Journal of Agricultural Research* 57: 347-354.

450 **Table 1.** Candidate rotations and associated labels.

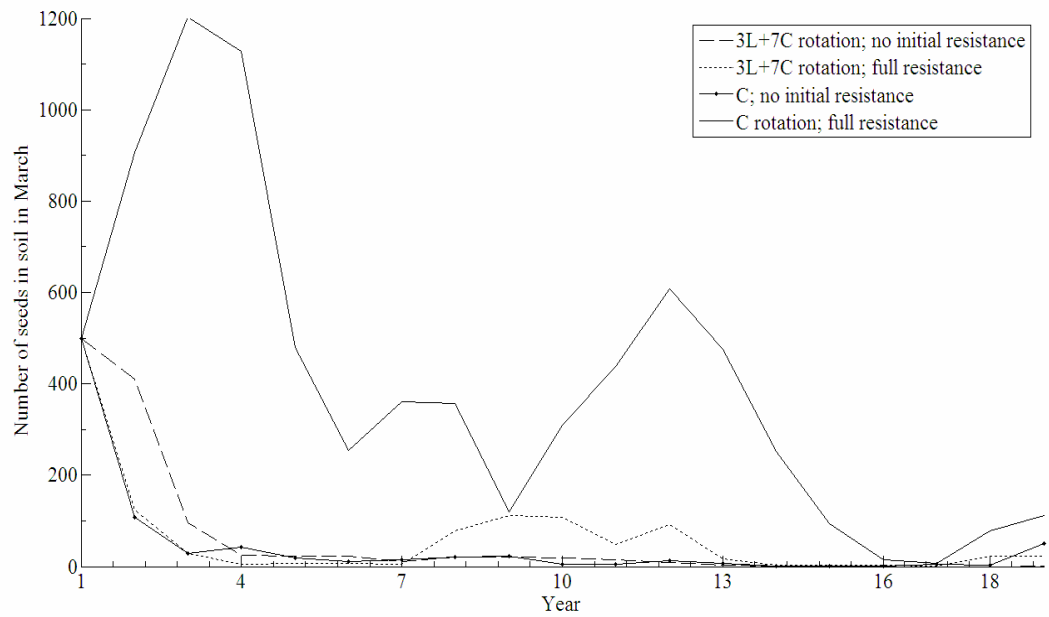| Rotation	Label
lupin-wheat-wheat-barley	*C*
serradella-wheat-wheat-barley	*S+3C*
lucerne-lucerne-lucerne-wheat-wheat-barley	*3L+3C*
serradella-wheat-wheat-barley-lupin-wheat-wheat-barley	*S+7C*
serradella-serradella-wheat-wheat-barley-lupin-wheat-wheat-barley	*2S+7C*
serradella-serradella-serradella-wheat-wheat-barley-lupin-wheat-wheat-barley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

451 **Table 2.** Value (NPV in A\$ ha^{-1}) of each rotation containing pasture relative to

452 continuous cropping over a range of initial seed densities. (Sheep gross margin A\$15

453 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

454 **Table 3.** Optimal integrated weed management strategies identified by compressed

455 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

456   **Figure 1.** Number of annual ryegrass seeds present in the soil at the beginning of the

457   growing season in two rotations at two different states of herbicide resistance. (Initial

458   seed density 500 seeds m^{-2})

459

460   **Table 4.** Value (NPV in A$ ha^{-1}) of each rotation relative to continuous cropping for a

461   range of sheep gross margins. (Initial seed density 500 seeds m^{-2}; no initial herbicide

462   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

463   [a]Base case.

464 **Table 5.** Value (NPV in A\$ ha^{-1}) of each rotation relative to continuous cropping for

465 alternative herbicide-resistance scenarios. (Initial seed density 500 seeds m^{-2}; sheep

466 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

467