CSIRO PUBLISHING
www.publish.csiro.au/journals/ajea *Australian Journal of Experimental Agriculture*, 2004, **44**, 1195–1203

The economic value of haying and green manuring in the integrated management of annual ryegrass and wild radish in a Western Australian farming system

M. Monjardino[A,B], *D. J. Pannell*[B] *and S. B. Powles*[A]

[A]Western Australian Herbicide Resistance Initiative, Faculty of Natural and Agricultural Sciences, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.
[B]School of Agricultural and Resource Economics, University of Western Australia, c/- WA Department of Agriculture, 444 Albany Highway, Albany, WA 6330, Australia.

Abstract. Most cropping farms in Western Australia must deal with the management of herbicide-resistant populations of weeds such as annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*). Farmers are approaching the problem of herbicide resistance by adopting integrated weed management systems, which allow weed control with a range of different techniques. These systems include non-herbicide methods ranging from delayed seeding and high crop seeding rates to the use of non-cropping phases in the rotation. In this paper, the Multi-species RIM (resistance and integrated management) model was used to investigate the value of including non-cropping phases in the crop rotation. Non-crop options investigated here were haying and green manuring. Despite them providing excellent weed control, it was found that inclusion of these non-cropping phases did not increase returns, except in cases of extreme weed numbers and high levels of herbicide resistance.

Introduction

Herbicide resistance has become a major problem in dryland cropping in Western Australia (WA), following the widespread and persistent use of herbicides for weed control. Contributing factors include the adoption of minimum and no-tillage systems, and reduced areas of pasture in favour of intensive cropping rotations. Persistent application of herbicides without the traditional weed control provided by cultivation and grazing has led to a high selection pressure for herbicide resistance on weed species such as annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) (Llewellyn and Powles 2001; Walsh *et al*. 2001). For several reasons, including resistance, these 2 species are the most widespread and economically damaging weeds in this cropping region.

Farmers are managing herbicide-resistant weed populations by adopting integrated weed management (IWM) systems, which allow weed control with a range of non-herbicide techniques along with changed herbicide usage (Powles *et al*. 1997). Non-herbicide methods range from delayed seeding and high crop seeding rates to seed catching at harvest and burning. Other options include the use of non-cropping phases in the rotation, for example the utilisation of a crop or pasture for hay, silage or manuring. Cutting for hay or silage can help in effective weed control before infesting weeds can produce seed. Another method used as a non-cropping phase is 'green manuring', which involves ploughing a growing crop or pasture (albeit weed infested) into the soil before any seed production can occur. Green manuring provides highly effective weed control, increased nutrient availability in the following year, and improved soil organic matter (Hoyle 1999), although the loss of a year's production involves a short-term economic sacrifice.

This study uses the bio-economic simulation model Multi-species RIM (resistance and integrated management) (Monjardino *et al*. 2003) to evaluate the value of haying and green manuring within a cropping-based system involving the integrated management of ryegrass and radish. In particular, the relationship between the current ryegrass and radish infestation and the long-term financial value of these practices is investigated. The focus is on 2 specific questions: (i) how large do the seed banks of annual ryegrass and wild radish need to be before it is worth introducing a non-cropping phase; and (ii) how do key biological and economic variables affect these break-even weed densities?

The hypothesis is that the inclusion of a non-cropping phase in the rotation (in this case haying or green manuring) only pays off when weed seed bank numbers are particularly high.

Materials and methods

Multi-species RIM model

Multi-species RIM is a bio-economic model that simulates the population dynamics of annual ryegrass and wild radish over a 20-year period. It is a decision support tool designed specifically for the evaluation of various management strategies to control herbicide-resistant weeds in dryland agriculture. The model includes a detailed representation of the biology of weeds, crops and pasture as well as the

 10.1071/EA03114 0816-1089/04/121195

financial costs and returns of agricultural production and management. The user specifies the cropping–pasture and management sequences for the 20-year period and the model calculates the consequences with respect to crop yields, weed populations, resistance status and profitability (Monjardino *et al*. 2003).

Weed biology. In the Multi-species RIM model, both weed seed production and expected crop yield after competition with the other species are calculated through the following equation first proposed by Firbank and Watkinson (1985) and later modified by Maxwell *et al*. (1990), and Diggle *et al*. (1994):

$$Y = \frac{m \times P_1}{a + P_1 + (k_{2.1} \times P_2) + (k_{3.1} \times P_3)} \quad (1)$$

where Y is weed seed production or grain yield after competition, P_1 is the density of species 1 (e.g. crop), P_2 is the density of species 2 (e.g. ryegrass), P_3 is the density of species 3 (e.g. wild radish), m is the maximum yield produced in the absence of competition, $k_{2.1}$ is the competition factor of species 2 on species 1, $k_{3.1}$ is the competition factor of weed species 3 on species 1, and a is the background competition factor (density at which yield is half of its potential maximum).

Parameter values for equation 1 are shown in Table 1, along with other key biological factors, such as germination, mortality and production of seed (per cohort and according to time of sowing), that drive the pattern of weed population change over time (Tables 2 and 3).

Enterprises. Multi-species RIM comprises a selection of 7 different enterprises, including four crops: wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), canola (*Brassica napus*) (assumed to be a triazine-tolerant variety) and lupins (*Lupinus angustifolius*); as well as 3 types of pasture for grazing by sheep: subterranean clover (*Trifolium subterraneum*), French serradella (*Ornithopus sativus* cv. Cadiz) and volunteer pasture (mixture of native species and volunteer crops and weeds). The sequence or rotation of crops and pasture over time is specified by the user. When any of these enterprises is chosen, production of grain, hay–silage or livestock–wool occurs. However, crop yield can be significantly reduced by weed competition. In addition, short rotations may affect potential crop yield (due to disease) as may some control methods, for example by delaying crop sowing or through phytotoxic damage by herbicides applied in-crop. Yield benefits provided by rotation with legume crops or pasture (due to nitrogen fixation) are also accounted for (Monjardino *et al*. 2003; Pannell *et al*. 2004). Levels of production from crops and pastures are typical of a dryland environment (Mediterranean-type climate) receiving 325–450 mm annual average rainfall.

Weed control. In the Multi-species RIM model there are 50 herbicide and non-herbicide control options available (for more details on each method, see Monjardino *et al*. 2003): (i) 27 crop-selective herbicide options for grass and broadleaved weeds (herbicides of high and moderate selection pressure); (ii) 6 non-selective herbicides (herbicides of low resistance risk); and (iii) 17 non-herbicide methods, including cultivation, delayed sowing, seed catching and stubble burning. Grazing during a pasture phase is another important non-herbicide option. Heavily weed-infested crops or pasture can be cut for hay–silage or used for green manuring.

The effect of each control strategy on weed mortality and seed set is specified for each enterprise (Monjardino *et al*. 2003). Gill and Holmes (1997), Gorddard *et al*. (1996), Powles *et al*. (1997), and Schmidt and Pannell (1996) have suggested that no one available method provides the optimal weed management strategy. Instead, a combination of a range of weed control methods can achieve very effective and sustainable weed control (IWM). Because control methods are conducted at different times, their combined impacts are considered to be multiplicative rather than additive (Pannell *et al*. 2004). However, where 2 herbicides are applied in a tank mix at the same time, there may be additive impacts (Kudsk 1989).

The Multi-species RIM model allows the user to specify the initial herbicide resistance status of ryegrass and wild radish with respect to each of 9 herbicide groups (modes of action).

Economic values. The model calculates costs, revenues, profit and net present value. It also includes complexities such as tax and long-term trends on prices and yields. Costs associated with cropping, pasture and various weed control options have been specified in detail. They account for costs of input purchasing; costs of machinery operating, maintenance and repayment; costs of contracting of labour for hay and silage making; and costs of crop insurance. There are also costs of crop yield penalty due to practices such as green manuring and delayed sowing, or contamination of the grain with wild radish seeds. Resource degradation costs associated with some non-herbicide methods such as cultivation and burning are also represented in the model. Economic returns from crops are based on sale prices for grain and hay. Net returns from sheep are specified as a long-term trend of gross margin per dry sheep equivalent ($11/dse), combining returns from wool and meat.

Table 1. Parameters used in the multi-species yield-density equations (source: statistical estimations provided by Diggle *et al*. 1994, Pannell *et al*. 2004 and these authors)

Species 1	Species 2	Species 3	P_1[A]	m[B]	a[C]	$k_{2.1}$[D]	$k_{3.1}$[D]
Wheat	Ryegrass	Radish	101–171	1.3	11	0.33	2.0
Barley	Ryegrass	Radish	129–214	1.4	10	0.3	1.7
Canola	Ryegrass	Radish	83–117	0.9	9.0	0.38	1.5
Lupins	Ryegrass	Radish	40–66	1.0	7.0	0.25	1.5
Ryegrass	Wheat	Radish	—	35000	33	3.0	6.0
Ryegrass	Barley	Radish	—	35000	33	3.3	6.0
Ryegrass	Canola	Radish	—	35000	33	2.6	4.0
Ryegrass	Lupins	Radish	—	35000	33	4.0	6.0
Radish	Wheat	Ryegrass	—	15000	9.0	0.50	0.17
Radish	Barley	Ryegrass	—	15000	9.0	0.60	0.17
Radish	Canola	Ryegrass	—	15000	9.0	0.67	0.25
Radish	Lupins	Ryegrass	—	15000	9.0	0.67	0.17

[A]Plant density (plants/m^2) is only indicated for crops as weed densities vary over the 20-year period.
[B]Maximum yield produced without competition is measured in t/ha for crops and in seeds/m^2 for weeds.
[C]Background competition factor in plants/m^2.
[D]Competition factors among species are non-dimensional.

Table 2. RIM parameters associated with population dynamics of annual ryegrass and wild radish

Biological variables	Ryegrass	Wild radish
Total germination during growing season (%)	82	30
Germination of cohort 1 (before 1st chance to seed) (%)[A]	5	4
Germination of cohort 2 (1–10 days after break) (%)[A]	38	12
Germination of cohort 3 (11–20 days after break) (%)[A]	23	8
Germination of cohort 4 (before in-crop herbicides) (%)[A]	14	5
Germination of cohort 5 (after in-crop herbicides) (%)[A]	2	1
Natural mortality of seedlings (% of total seedlings)	2	2
Natural mortality of dormant seeds during season (%)	20	5
Natural mortality of seeds over summer (%)	30	10

[A]Germination refers to percentage of total initial seed bank.

Because the model is run over 20 years (t), annual net profit (ANP) must be discounted to make it comparable at the start of the modelled period. A real discount rate (r) of 5% per year is used for this purpose. The sum of discounted net profits or net present value (NPV) is the main economic criterion used to compare weed management strategies (equation 2). In results presented later it is expressed in an annualised form on a per hectare basis (annuity):

$$NPV = \sum_{i=1}^{n} \frac{ANP}{(1+r)^t} \quad (2)$$

Weed management scenarios

Enterprise sequences. The value of non-cropping phases in the rotation was investigated for the following examples of enterprise sequences: (*a*) a barley–lupin–wheat–wheat rotation (BLWW); and (*b*) a barley–lupin–wheat–wheat rotation with a single 3-year French serradella pasture phase in years 9–11 (BLWW+ PPP) (thus 2 sequences of BLWW before the 3-year pasture phase).

The value of haying was evaluated when cut from barley in the first year only of the 20-year period of both rotations.

The analysis examined the value of green manuring lupins in the second year only of the 20-year period of both rotations. The fact that lupin grain is less valuable (in terms of gross returns per hectare) than that of cereals or canola, and that vegetative lupins have a high nitrogen content, means that lupins are better suited for green manuring than any of the other crops represented in multi-species RIM. Therefore, the rotations were arranged in such a way that lupins were always the green-manured crop in year 2 of the 20-year sequence. The single pasture phase in rotation (*b*) was investigated, because it provides an alternative to the more radical approach of green manuring. A 3-year pasture phase allows for high levels of weed control without the use of selective herbicides, so this is likely to diminish the value of green manuring relative to an analysis based on continuous cropping.

The model was set at 400 ryegrass and 100 wild radish seeds/m^2 at the start of the simulation for all weed management scenarios. These densities are considered average values across the field. The impact of different initial weed seed densities is investigated later in the paper.

Herbicide use. All cropping and pasture rotations were investigated for a scenario of herbicide use where a maximum of 2 herbicide applications of groups A and B (each) were available before complete herbicide resistance evolved in both ryegrass (groups A and B) and wild radish (group B). For all rotational scenarios, it was assumed that there were up to 10 applications available of each moderate-risk herbicide group (C, D, F and G) and up to 15 applications available of each low-risk herbicide group (I, L and M). These assumptions about herbicide resistance status assume a past history of herbicide use in the field. See Appendix 1 for a more detailed description of the herbicides used in the model.

Non-herbicide methods. Complementing the strategies of haying, green manuring and herbicide application, many combinations of other control methods were investigated in order to find the best management systems. The range of IWM methods employed across the 6 rotational strategies is listed in Table 4.

These strategies were identified in a simulation process of 'trial and error' and were selected on the basis of the optimal 20-year profit based on numerous simulation runs with different combinations of weed management parameters. A purposeful sample of all possible combinations of decision settings is the complete factorial analysis conducted below on the value of green manuring, resulting in the frequency distribution of net values. For the purpose of this study, the term 'optimal' refers to the strategy that produces the highest long-term profit (annuity) from within the dataset.

Results and discussion

As shown in Table 4, all applications of groups A and B were used in the rotational sequences investigated. The use of simazine (group C) was generally greatest in rotations with a higher proportion of lupins. No more than 2 uses of groups D (trifluralin) and F and zero uses of group G were

Table 3. Seed production indices representing seed production by different cohorts of ryegrass (RG) and wild radish (WR), relative to seed produced by healthy (early germinating) weed plants

Weed emergence relative to time of crop sowing	Time of sowing					
	Day 0		Day 10		Day 20	
	RG	WR	RG	WR	RG	WR
Weeds emerging 1–10 days after break	1	1	1	1	1	1
Weeds emerging 11–20 days after break	0.3	0.5	1	1	1	1
Additional weeds emerging before in-crop control	0.1	0.1	0.3	0.5	0.3	0.5
Weeds emerging after in-crop control	0.02	0.02	0.02	0.02	0.02	0.02

Table 4. Number of uses of each weed management method across all rotations

IWM methods	BLWW	B^A^LWW	BL^B^WW	BLWW+PPP	B^A^LWW+PPP	BL^B^WW+PPP
Glyphosate-knockdown (M)	12	12	12	4	4	6
Group A herbicides	2	2	2	2	2	2
Group B herbicides	2	2	2	2	2	2
Group C herbicides	8	8	8	10	10	8
Group D herbicides	1	1	1	2	2	2
Group F herbicides	2	2	2	0	0	0
Group I herbicides	15	15	15	13	13	13
High crop seeding rate	19	19	19	15	15	15
Tickle + 20-day delay seeding	4	4	4	3	3	2
Sustainable grazing	0	0	0	1	1	1
High-intensity grazing	0	0	0	2	2	2
Pasture spraytopping (L/M)	0	0	0	3	3	3
Lupins croptopping (L)	5	0	4	4	4	3
Green manuring	0	0	1	0	0	1
Cutting for hay	0	1	0	0	1	0
Swathing	4	4	4	3	3	3
Seed catching + burning	11	10	11	9	8	9
Windrowing + burning	8	8	7	6	6	5
Residues burning	0	0	0	1	1	1

[A] Haying barley in year 1 of the rotation only. [B] Green manuring lupins in year 2 of the rotation only.

selected in the economically preferred management systems identified.

The weed management strategy remained relatively constant across all rotations. Obvious differences were a decrease in the use of high crop seeding rates and harvest techniques in all rotations with any pasture. A decrease in the practice of delayed seeding was observed when more pasture was grown. Only minor differences were found between the strategies including and excluding hay or green manuring. An exception, however, was the non-use of croptopping (paraquat applied in-crop late in the growing season in lupins), swathing, seed-catching and windrowing in those crops that were sacrificed in the process of haying or green manuring.

Table 5 shows the average annual returns over 20 years (annuities) and the final weed plant densities across all systems considered in this study. The best rotation in financial terms was the continuous cropping sequence, BLWW ($117/ha.year), closely followed by the same BLWW rotation with a 3-year pasture phase once during the 20-year simulation ($113/ha.year, respectively). Next in rank was the same continuous cropping sequence (BLWW), but with haying in the first year or green manuring in the second year ($108 and $106/ha.year, respectively). Weed numbers were kept low across most scenarios.

Haying

Net value of haying. The potential value of cutting a crop for hay so as to achieve zero weed seed production in that year was examined in the rotations BLWW with and without including a 3-year pasture phase in years 9–11. In both cases, barley was cut for hay in the first year of the 20-year sequence. As shown in Table 6 (based on Table 5), the haying phases in BLWW and BLWW+ PPP generated negative net values of –$9 and –$10/ha.year, respectively.

Figure 1 illustrates the change in annual gross margins over the 20-year period for the BLWW rotation, with and without haying (results for BLWW+ PPP are similar). As expected, there was a significant difference in gross margins between the first year of the rotation with and without haying

Table 5. Annuities and final weed densities across all rotations

Rotation	Annuity ($/ha.year)	Ryegrass density in year 20 (plants/m^2)	Radish density in year 20 (plants/m^2)
BLWW	117	4	<1
BLWW, barley cut for hay[A]	108	1	<1
BLWW, green-manured lupins[B]	106	1	<1
BLWW+ PPP	113	1	1
BLWW+ PPP, barley cut for hay[A]	103	<1	1
BLWW+ PPP, green-manured lupins[B]	105	4	1

[A] Year 1 only. [B] Year 2 only.

Table 6. Annuities ($/ha.year) and net value ($/ha.year) of haying for two rotations with and without barley cut for hay in year 1

	BLWW	BLWW+ PPP
With haying	108	103
Without haying	117	113
Net value of haying	–9	–10

(–$114/ha/year) due to the loss of barley yield in that year. The barley would be harvested in the non-haying rotation (giving a net return of $61/ha.year). The benefits in later years from the haying operation in year 1 were small and clearly not sufficient to outweigh the large cost in year 1.

Initial weed seed densities. A sensitivity analysis on the initial weed seed densities was further conducted for BLWW, with and without haying in year 1 of the rotation. The results (data not shown) indicate that the value of haying increased by $1–2/ha.year as the initial ryegrass seed bank went from 400 to 1600 seeds/m^2, whereas it decreased by $1/ha.year when the radish seed bank was highest (400 seeds/m^2). These results indicate that haying is a more useful tool against ryegrass than against wild radish infestations. This is probably because of the lower seed dormancy of ryegrass, which allows haying to have a greater and more enduring effect on the seed bank.

Herbicide resistance status. Several scenarios of resistance status were investigated for the BLWW rotation in order to determine how the value of haying was affected by the level of herbicide resistance to all herbicide groups. Results are shown in Table 7, where each column (I to VI) corresponds to a scenario involving a defined number of applications of each herbicide group (rows A to M).

As herbicide use was reduced, the value of haying increased by $9/ha.year across scenarios I to IV. The lower values obtained for haying in the last 2 scenarios (V and VI) result from a general low level of returns for both rotations, as weed control becomes very difficult to achieve with hardly any herbicides available. These results show that cutting a crop for hay in a long-term sequence may make a valuable contribution to profitability in situations of low herbicide availability due to herbicide resistance.

Break-even values. A simple break-even analysis was conducted on the sale price of hay for the rotations BLWW and BLWW+ PPP, with the first barley phase cut for hay. The hay option represented in RIM is assumed to be primarily for weed control, not hay of export quality (usually from oats) reaching high prices in the market. In this analysis it was found that the sale price of hay would have to increase from $26/t (model default price) to $56/t in BLWW and to $70/t in BLWW+ PPP for these scenarios to be as profitable as the continuous cropping sequence. Such a large increase in the price of hay is highly unlikely. So haying is likely to remain a relatively unattractive practice for most farmers across WA. Even if its weed control efficacy changed from 95 to 100%, the rotational value of haying would only increase by about $0.1/ha.year, which is not sufficient to justify its inclusion.

Green manuring

Green manuring was investigated for the rotations BLWW with and without including a 3-year pasture phase in years 9–11.

Weed densities. An example of model results showing variation in annual ryegrass and wild radish plant infestation in BLWW is illustrated in Figure 2. Notably, the final weed densities in year 2 are similar with or without the use of green manuring. This may be considered surprising, given that manuring is such a highly effective means of weed control. However, in the non-manuring strategy, effective control is achieved by a combination of herbicides (simazine and Gramoxone croptopping) and windrowing. This is much cheaper than green manuring, but it means that this application of simazine is not available for later use. Its loss is covered by other control measures in later years.

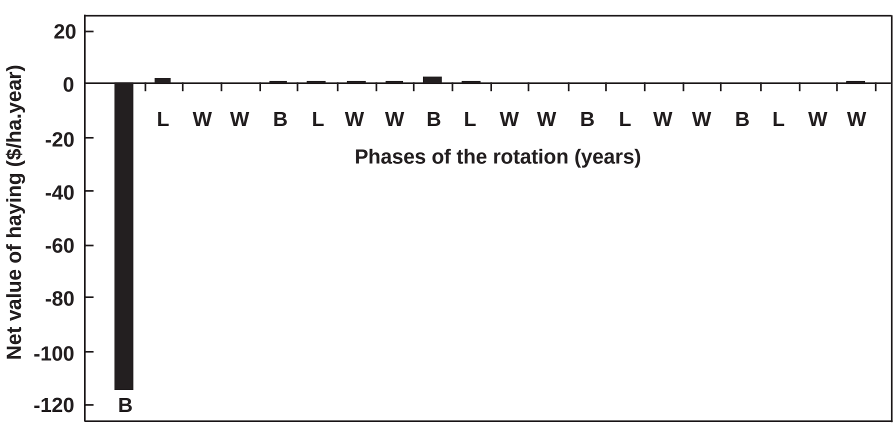

Figure 1. Difference in annual gross margins over the 20-year period between a barley–lupin–wheat–wheat rotation with and without barley cut for hay in year 1.

Table 7. Effect of herbicide use on the net value of haying ($/ha.year) for a barley–lupin–wheat–wheat rotation

Each column (I to VI) corresponds to a scenario involving a defined number of applications left before full resistance of each herbicide group (rows A to M)

Herbicide group	Herbicide resistance scenarios (no. of applications remaining before full resistance)					
	I	II	III	IV	V	VI
A	2	2	0	0	0	0
B	2	2	0	0	0	0
C	10	4	4	2	0	0
D	10	4	4	2	0	0
F	10	4	4	2	0	0
I	15	15	5	5	5	0
L	15	15	5	5	5	0
M	15	15	5	5	5	0
Net value of pasture ($/ha.year)	–9	–5	–3	0	–3	–3

Net value of green manuring. Table 8 (based on Table 5) shows the net value of green manuring in both rotations, calculated as the difference in annuity between the results with and without green-manured lupins in year 2. Based on standard parameter values, green manuring was not an attractive practice, with negative net values of –$11 and –$13/ha.year. As for haying, the inclusion of a 3-year pasture phase diminished the value of green manuring relative to the continuous cropping sequence, due to the effective weed control provided by grazing and the use of non-selective herbicides.

Figure 3 indicates that gross margins were higher in the year after lupins were green-manured in year 2 of the rotations. The increase in gross margin was mainly limited to the first wheat year following the green manuring phase ($16/ha.year), and it was not sufficient to outweigh the up-front costs.

The negative value of green manuring results mainly from the combination of negative and positive influences from 4 factors: (i) direct cost and lost income due to green manuring in year 2 of the rotation; (ii) changes in weed

Table 8. Annuities ($/ha/year) and net value ($/ha.year) of green manuring for two rotations with and without green-manured lupins in year 2

	BLWW	BLWW+ PPP
With green manuring	106	100
Without green manuring	117	113
Net value of green manuring	–11	–13

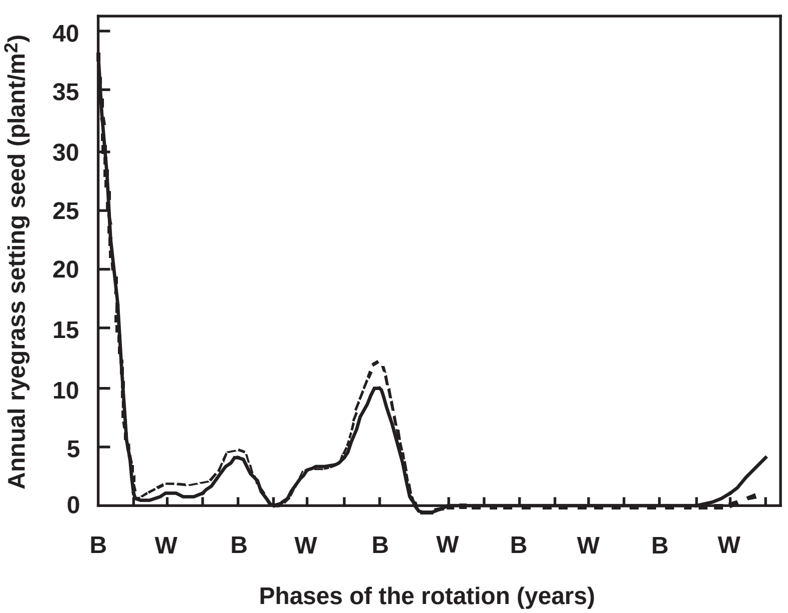

Figure 2. Annual ryegrass densities over 20 years for a barley–lupin–wheat–wheat rotation with and without green-manured lupins in year 2.

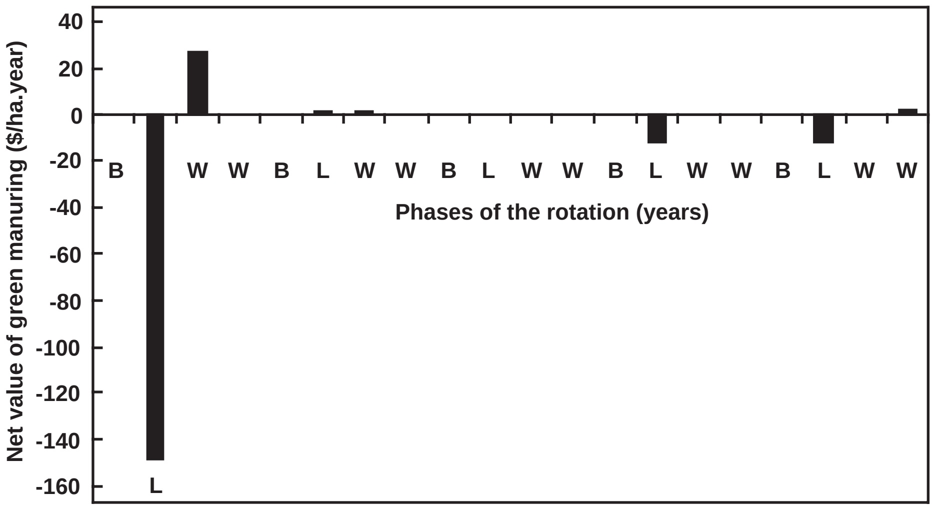

Figure 3. Difference in annual gross margins over the 20-year period between a barley–lupin–wheat–wheat rotation with and without green-manured lupins in year 2.

control direct costs other than green manuring; (iii) changes in weed competition over all years; and (iv) greater availability of nitrogen in crops following green manuring.

A total of $168/ha in direct costs and foregone income due to green manuring in year 2 was incurred to both sequences, which is equivalent to a $14.10 reduction in the annuity. Of that amount, $2.10 annuity was due to the direct cost of the green manuring operation (including cost of machinery, fuel and risk of erosion) and $12 annuity was due to the yield loss of the lupin crop. On the positive side, including green manuring in the rotations led to a reduction in direct weed control costs of $0.41 for BLWW. Finally, benefits of $2.8 annuity in the cropping rotation and of $0.08 annuity in the pasture sequence were attributed to the combined value of (*a*) the positive effects of green manuring on the subsequent crop yields, and (*b*) reduced weed competition over the whole 20-year period.

Sensitivity analysis. As the value of green manuring is likely to depend on the severity of weed infestations, the initial ryegrass and radish seed bank numbers were varied. Furthermore, given the importance of weed seed germination when analysing the profitability of a practice like green manuring, a sensitivity analysis on the annual seed bank decline of both ryegrass and radish was conducted. Several levels of green manuring control efficacy were tested. Finally, 2 levels of lupin weed-free

Table 9. Values of uncertain parameters used in the green manuring analysis

Parameters	Zero value	Minimum value	Standard value	Maximum value
Ryegrass initial seed density (seeds/m^2)	0	100	400[A]	1600
Radish initial seed density (seeds/m^2)	0	25	100[A]	400
Ryegrass annual germination (%)		70	80[A]	90
Radish annual germination (%)		20	30[A]	40
Green manuring control efficacy (%)		95	98[A]	100
Lupin weed-free yield (t/ha)			1[A]	1.5

[A]Model default values.

Table 10. Probability of occurrence of each parameter level

Parameters	Zero value	Minimum value	Standard value	Maximum value
Ryegrass initial seed density	0.05	0.2	0.5	0.25
Radish initial seed density	0.05	0.2	0.5	0.25
Ryegrass annual germination	—	0.15	0.7	0.15
Radish annual germination	—	0.15	0.7	0.15
Green manuring control efficacy	—	0.15	0.7	0.15
Lupin weed-free yield	—		0.85	0.15

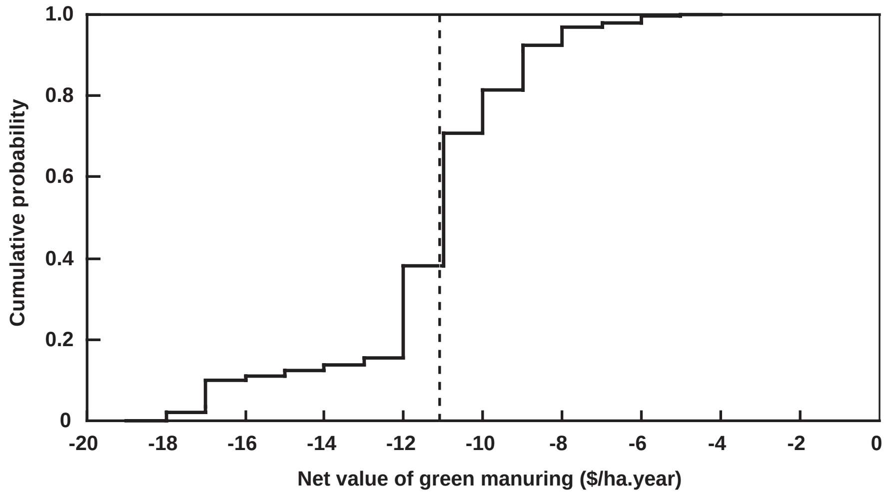

Figure 4. Cumulative distribution function for the net value of green manuring in a barley–lupin–wheat–wheat rotation.

yield were evaluated. A list of the 6 uncertain parameters and their value ranges used in this sensitivity analysis is shown in Table 9.

The sensitivity analysis on the value of green manuring included a complete factorial analysis with the four weed-related parameters, the control efficacy of green manuring and the weed-free yield of lupins (Table 9). It produced 864 solutions ($4^2 \times 3^3 \times 2$) with and 864 solutions without green manuring. Subjectively assigning a probability to each of the 864 net value solutions (Table 10) allows the identification of the frequency distribution of the net value of green manuring (Fig. 4).

Figure 4 demonstrates that the net value of green manuring is negative (below –$4/ha.year) in all scenarios investigated. About 80% of the scenarios have a net value lower than –$10/ha.year, with the majority assuming values between –$10 and –$12/ha.year (the mode is –$12/ha.year). The mean of the distribution is –$11.4/ha.year (dashed line) and the median is –$11/ha.year. These results indicate that in this farming system green manuring is generally an unprofitable practice in a continuous cropping situation, particularly when weed numbers are kept low. It appears that other weed control methods are available which can substitute for green manuring at lower cost.

Conclusion

The Multi-species RIM model was used to evaluate the value of including non-cropping phases in the rotation. For this farming system, under the scenarios considered, the inclusion of non-cropping phases such as haying and green manuring was generally found to reduce profits relative to the most profitable continuous cropping sequence. This was despite the fact that most of the evaluated non-cropping options led to very good weed control over the 20-year period.

Results indicate that a haying year in the rotation is a more useful tool against ryegrass than against wild radish infestations, and that it becomes more valuable as initial ryegrass numbers increase. Nevertheless, with a break-even hay sale price above $30/t, cutting crops for hay for weed control remains an unattractive practice for farmers in the farming system modelled.

In the sensitivity analysis of green manuring, about 80% of the scenarios investigated showed a net value lower than –$10/ha.year. However, green manuring does provide very effective weed control and its value increases as the weed burden increases in the system, especially for the dominant weed species (wild radish in this case). The most promising prospects for green manuring appear to be in cases of extreme herbicide resistance, involving the loss of all selective herbicides.

Acknowledgments

The authors acknowledge the contribution of A. Draper, R. Llewellyn and M. Walsh in reviewing this paper. The Grains Research and Development Corporation and the Cooperative Research Center for Weed Management Systems provided financial support for this research.

References

Diggle AJ, Gill GS, Holmes JE (1994) Delaying the development of herbicide resistant *L. rigidum* by using alternative weed control strategies. Report No. 14/93, Agriculture Western Australia, Perth.

Firbank LG, Watkinson AR (1985) On the analysis of competition within two-species mixtures of plants. *Journal of Applied Ecology* **22**, 503–517.

Gill GS, Holmes JE (1997) Efficacy of cultural control methods for combating herbicide-resistant *Lolium rigidum*. *Pesticide Science* **51**, 352–358. doi:10.1002/(SICI)1096-9063(199711)51:3<352::AID-PS648>3.0.CO;2-M

Gorddard RJ, Pannell DJ, Hertzler G (1996) Economic evaluation of strategies for management of herbicide resistance. *Agricultural Systems* **51**, 281–298. doi:10.1016/0308-521X(95)00047-9

Hoyle F (1999) 'Green manuring a new focus for cropping.' (Department of Agriculture of Western Australia: South Perth)

Kudsk P (1989) Experiences with reduced herbicide doses in Denmark and the development of the concept of factor adjusted doses. In 'Proceedings of the Brighton crop protection conference — weeds'. pp. 545–554. (British Crop Protection Council: Brighton, UK)

Llewellyn RS, Powles SB (2001) High levels of herbicide resistance in rigid ryegrass (*Lolium rigidum*) in the wheatbelt of Western Australia. *Weed Technology* **15**, 242–248.

Maxwell BD, Roush ML, Radosevich SR (1990) Predicting the evolution and dynamics of herbicide resistance in weed populations. *Weed Technology* **4**, 2–13.

Monjardino M, Pannell DJ, Powles SB (2003) A multi-species bio-economic model for management of *Lolium rigidum* and *Raphanus raphanistrum* in Australian cropping systems. *Weed Science* **51**, 798–809.

Pannell DJ, Stewart V, Bennett A, Monjardino M, Schmidt C, Powles S (2004) RIM: a bio-economic model for integrated weed management. *Agricultural Systems* **79**, 305–325. doi:10.1016/S0308-521X(03)00089-1

Powles SB, Preston C, Bryan IB, Jutsum AR (1997) Herbicide resistance: impact and management. *Advances in Agronomy* **58**, 57–98.

Schmidt C, Pannell DJ (1996) Economic issues in management of herbicide-resistant weeds. *Review of Marketing and Agricultural Economics* **64**, 301–308.

Walsh MJ, Duane RD, Powles SB (2001) High frequencey of chlorsulfuron resistant wild radish (*Raphanus raphanistrum* L.) populations across the Western Australian wheatbelt. *Weed Technology* **15**, 199–203.

Received 15 July 2003, accepted 5 March 2004

Appendix 1. Herbicides included in the Multi-species RIM model for each weed species

The letters under each weed indicate the enterprises to which the herbicide is applicable (a dash indicates that the herbicide is not an option for this weed)
W, wheat; B, barley; C, canola; L, lupins; P pasture

Chemical group	Herbicide description	Ryegrass	Wild radish
	Non-selective herbicides		
M	Glyphosate as knockdown and pasture-topping	W, B, C, L, P	W, B, C, L, P
L	Spray.Seed knockdown	W, B, C, L, P	W, B, C, L, P
	Gramoxone lupins/pasture-topping	L, P	L, P
M + L	2 × knockdown with glyphosate + Spray.Seed	W, B, C, L, P	W, B, C, L, P
	Selective herbicides		
A	Hoegrass	W, B, C, L, P	—
	Fusilade	C, L, P	—
	Select	C, L, P	—
	Other Dim for lupins or canola	L, C	—
B	Glean (pre- and post-emergence)	W	W, B
	Logran (pre- and post-emergence)	W	W, B
	Eclipse	—	W, B, L
	Broadstrike	—	W, B, P
	Spinnaker	L, P	—
	OnDuty	C	C
C	Simazine (pre- and post-emergence)	C, L, P	C, L, P
	Atrazine (pre- and post-emergence)	C	C
	Atrazine + simazine (pre-emergence)	L	L
D	Trifluralin	W, B, C, L	—
F	Brodal	—	L, P
I	2,4-D Amine	—	W, B, P
	2,4-D Ester	—	W, B
C + I	Buctril MA	—	W, B
	Diuron + MCPA	—	W, B, L
C + F	Lexone + Brodal	L	L
	Jaguar	—	W, B. P
I + F	Tigrex	—	W, B, P
G + I	Affinity + MCPA	—	W, B