THE VALUE OF ROUNDUP-READY® CANOLA IN THE MANAGEMENT OF TWO WEEDS

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ABSTRACT

The Multi-species RIM (Resistance and Integrated Management) model is used in this analysis to investigate the value of Roundup-Ready® canola in the simultaneous management of annual ryegrass (*Lolium rigidum)* and wild radish (*Raphanus raphanistrum*). It is likely that the transgenic canola variety resistant to the non-selective herbicides glyphosate will soon be introduced in Australian agriculture. The perceived advantage of growing these crops is the potential to control post-emergent weeds with excellent broad-spectrum herbicides, and without the yield penalty evident in triazine-resistant canola (grown widely in WA). This may also help prolong the life of selective herbicides, to which ryegrass and radish can be highly resistant. Therefore, the introduction of genetically modified glyphosate-resistant canola will, other factors being equal, not only increase the options for weed control, but increase the yield of the vast canola crops grown in WA. Conversely, increased usage of the herbicide to which the new crop is resistant can result in the evolution of resistance to that herbicide in weeds. These trade-offs are discussed here.

Keywords: Roundup-Ready® canola, Multi-species RIM, herbicide resistance.

INTRODUCTION

Approximately one million hectares of canola are grown annually in Western Australia. Because weed control (especially wild radish) is critical to achieving a viable canola harvest and wild radish is a major and extensive problem in Western Australia, almost all of the canola grown in WA is of a triazine tolerant variety. It contains a gene endowing resistance to the triazine herbicides (e.g. atrazine and simazine). These herbicides provide control of wild radish, annual ryegrass and other weed species selectively in canola. However, the presence of the triazine-resistance gene (selected by traditional breeding methods) results in a 10 to 20 percent crop yield penalty (and 2 to 3 percent lower oil content) relative to the best varieties that lack triazine tolerance (Holt and Thill, 1994; Moore and Carmody, 1997; GM Canola Technical Working Group, 2001). In addition, the herbicide atrazine is a soil active residual herbicide, with risks of carryover and damage to following cereal crops under low rainfall conditions (GM Canola Technical Working Group, 2001).

It is likely that transgenic canola varieties resistant to broad-spectrum, otherwise non-selective herbicides, glyphosate or glufosinate will soon be introduced in Australian agriculture. The perceived advantage of growing these crops is the potential to control post-emergent weeds with excellent broad-spectrum herbicides, and without the yield penalty evident in triazine-resistant canola. This may also reduce reliance and thus help prolong the life of selective herbicides, to which ryegrass and radish can be highly resistant. Therefore, the introduction of genetically modified glyphosate- or glufosinate-resistant canola will, other factors being equal, not only increase the options for weed control, but increase the yield of canola crops grown in WA. Conversely, increased usage of a herbicide to which the new crop is resistant can result in the evolution of resistance to that herbicide in weeds. These trade-offs are discussed here.

This analysis investigates the use of Roundup-Ready® canola (RR-canola), which has been genetically modified to become resistant to glyphosate (Roundup®). It is assumed that, not only can glyphosate be sprayed in-crop up to two times, but RR-canola is also expected to perform better than triazine-tolerant canola (TT-canola) (default canola crop in the Multi-species RIM model) in terms of yield and competition against weeds. Conversely, GM canola seed is likely to be priced higher than that of other genotypes (due to a technology fee).

Controversial issues associated with genetically modified crops relate to food quality, environmental impact, risks of gene flow and marketing, as discussed by Smith *et al*. (2000). However, none of those issues are investigated in this study.

THE MULTI-SPECIES RIM MODEL

The Multi-species RIM (Resistance and Integrated Management) 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 of the economics of agricultural production and management (Monjardino *et al*., 2002).

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:

$$Y = \frac{(P_O + a)}{P_O} \times \frac{P_1}{a + P_1 + (k_{2.1} \times P_2) + (k_{3.1} \times P_3)} \times M + (1 - M) \qquad (1)$$

Where,

Y = Weed seed production or proportion of grain yield after competition
P_0= Reference density of the crop at standard seeding rate
P_1= Density of species 1 (eg. crop)
P_2 = Density of species 2 (eg. ryegrass)
P_3 = Density of species 3 (eg. wild radish)
$k_{2.1}$ = Competition factor of species 2 on species 1
$k_{3.1}$ = Competition factor of weed species 3 on species 1
a = Background competition factor (plant density at which yield loss is half the maximum yield loss, i.e. density at which: $1 - PGY = M/2$)
M = Maximum proportion of grain yield lost at very high weed densities

The parameter values for Equations 1 are shown in Appendix 1. Other biological key factors that drive the pattern of weed population change over time are shown in Appendices 2 and 3.

Enterprises

At present Multi-species RIM comprises a selection of seven different enterprises, including four crops (wheat, barley, TT canola and lupins), as well as three types of pasture for grazing by sheep (sub-clover, cadiz serradella and volunteer pasture). The sequence or rotation of crops and pasture over time can be specified by the user. When any of these enterprises is chosen, production of grain, hay/silage or wool occurs. However, crop yield can be significantly reduced by weed competition. In addition, short rotations (due to disease) and some control methods may affect potential crop yield, 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 (Pannell *et al*., 2001; Monjardino *et al*., 2002).

Weed control

In the Multi-species RIM model there are 50 chemical and non-chemical control options available (for more details on each method, see Monjardino *et al*., 2002):

- **27** selective herbicides for grass and broadleaved weeds, which provide very effective weed control, but result in a strong selection pressure for resistance when applied continuously (Powles *et al*., 1997).
- **6** non-selective herbicides. In spite of their widespread application, there are only relatively few cases reported of resistance to non-selective herbicides. Powles *et al.* (1997) suggest that this is an indication that resistance gene frequencies for such herbicides are low.
- **17** non-chemical methods, varying from cultivation and delayed sowing to seed catching and stubble burning. Grazing during a pasture phase is another important non-chemical option. Heavily weed-infested crops or pasture can be cut for hay/silage or used for green manuring.

Each control strategy has its own impact on weed mortality and seed set (Appendix 4). However, Gorddard *et al*. (1996), Matthews (1996), Schmidt and Pannell (1996), Gill and Holmes (1997), and Powles *et al*. (1997) suggest that no one method available provides the optimal management strategy for herbicide-resistant weeds. Instead, only a combination of a wide range of weed control methods can achieve very effective and sustainable weed control (integrated weed management, IWM). Because control methods are conducted at different times, their combined impacts are considered to be multiplicative rather than additive (Pannell *et al*., 2001)[1].

The Multi-species RIM model further allows the user to specify the herbicide resistance status of the ryegrass and wild radish weeds with respect to each of nine 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 estimated 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 due to crop grain contamination with wild radish seeds. Resource degradation costs associated with some non-chemical methods such as cultivation and burning are also represented in the model. Economic returns from crops and stock are based on grain, hay and wool yields and sale prices. Sheep value is given as a gross margin per DSE.

Because the model is run over 20 years (T), annual net profit must be discounted to make them comparable to the start of the 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 shown in the following equation:

$$NPV = \sum_{t=1}^{T} \frac{TR - TC}{(1+r)^t} \qquad (2)$$

Where:

NPV = Net present value

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[1] Strictly, the proportions surviving treatment are multiplicative for multiple control methods.

TR = Total return
TC = Total costs
t = Period considered (up to T = 20 years)
r = Real discount rate (5%)

The model does not optimise, but is used to simulate a wide range of potential treatment strategies, so that an overall strategy which is at least near-optimal can be identified.

WEED MANAGEMENT SCENARIOS

Enterprise sequences

The value of RR-canola was investigated for three WA farming scenarios over 20 years:

a) A continuous cropping wheat-wheat-canola-wheat-lupin rotation (WWCWL) using RR-canola, which allows for extra applications of glyphosate after crop emergence and before seed set (crop-topping).
b) A continuous cropping wheat-wheat-canola-wheat-lupin rotation (WWCWL) using TT-canola, with the traditional use of glyphosate before crop seeding.
c) A wheat-wheat-canola-wheat-lupin rotation punctuated by a 3-year phase of cadiz serradella pasture in years 9-11 (WWCWL+ PPP). In this scenario the canola crop used was TT-canola (hence no glyphosate was applied in-crop), but the usage of glyphosate was again increased by pasture applications in spring (spray-topping) in each year of the pasture phases.

The selected enterprise sequences were considered to be representative of the WA farming system, where wheat is the main crop grown, lupins and pasture are included for their yield-boosting ability, and canola is commonly grown once in a five-year rotation as a “break crop” (it provides an effective break to cereal diseases) and for its market value. The inclusion of a pasture phase in the rotation was only intended to provide a comparison with the cropping sequences in terms of weed management.

Herbicide use

The herbicide resistance status of the weeds is dealt with in Multi-species RIM through defining the number of applications of each herbicide group left available before the onset of resistance. For both weed species, a maximum of five applications was allowed for herbicides of high resistance risk (Groups A and B), 10 for herbicides of moderate resistance risk (Groups C, D, F and G), and 15 for herbicides of low resistance risk (Groups I, L and M), to which glyphosate belongs. Table 1 summarizes the strategies for each scenario.

As shown in Table 1, no applications of Group A herbicides were used in Scenario 1 (RR-canola) and only one application was economically used in each of Scenario 2 and Scenario 3 (TT-canola). Nearly all five Group B herbicide applications were used up in the three scenarios (Scenario 2 had only four applications). As expected, the use of Group C herbicides was greatest in the pasture scenario (due to extra applications in the pasture phase) and least in the RR-canola rotation, where no triazine herbicides (atrazine, simazine) are allowed. Similar use of other moderate- and low-risk herbicides was observed across all scenarios, except for glyphosate, which had significantly higher use in RR-canola and pasture.

Non-herbicide methods

For all scenarios, the most profitable combination of several non-herbicide methods was identified to best complement herbicide use, as shown in Table 1. These practices were selected using a lengthy process of trial and error within the model. In general, these strategies included practices such as high crop seeding rates and, in some years, a shallow cultivation followed by delayed crop seeding (mostly 20 days). During crop harvest, swathing of canola was often profitable and practices like seed catching and windrowing were attractive control methods. Pasture was grazed moderately (first year) and intensely (second and third years) and its residues burnt in the last year of that phase. Overall, replacement of TT-canola by RR-canola meant lower reliance on delayed crop seeding and harvest techniques for effective weed control.

Table 1 Strategies and implications of using RR-canola versus TT-canola. The number of applications of each control method is shown in brackets.

Strategies	Scenario 1	Scenario 2	Scenario 3
Enterprise sequence	WWCWL	WWCWL	WWCWL+ PPP
Canola genotype	RR-canola	TT-canola	TT-canola
Applications of high-risk herbicides	0A; 5B; 4.5C (no triazines)	1A; 4B; 8.5C	1A; 5B; 10C
Applications of moderate-risk herbicides	0D; 5.5F; 0G	0D; 6.5F; 0G	0D; 4F; 0G
Applications of low-risk herbicides	13I; 3L; 15M	14I; 3L; 12M	11I; 3L; 12M
Total applications of glyphosate	15	9	12
Profitable non-herbicide weed control methods	• Tickle, delayed seeding 20 days (0) • High crop seeding rates (19) • Swathing (5) • Seed catching + burning (0) • Windrowing + burning (3)	• Tickle, delayed seeding 20 days (2) • High crop seeding rates (20) • Swathing (4) • Seed catching + burning (2) • Windrowing + burning (7)	• Tickle, delayed seeding 20 days (1) • High crop seeding rates (17) • Swathing (4) • Seed catching + burning (3) • Windrowing + burning (7) • Burning (1) • Grazing (1) • High intensity grazing (2)

ANALYSIS DESIGN

In the case where RR-canola was used (Scenario 1), modifications to the model in order to conduct this analysis involved the following:

a) Adding glyphosate for use post-emergence and before seed set in spring. Associated cost, rate (1 L ha^{-1}) and efficacy were also included.
b) Adding a technology fee to the standard canola seed price.
c) Including a RR-canola yield advantage relative to TT-canola.

However, due to lack of information on the GM canola variety, these parameters were subjected to a sensitivity analysis for Scenario 1 and Scenario 2. The values of 80 and 100 percent reduction of ryegrass and radish plant/seed numbers were used to bracket the most likely range of weed control by glyphosate in-crop. The flat technology fee added to the standard crop seed price was set at values of \$30 and \$50 ha^{-1} (S. Powles, WAHRI, pers. comm., 2001). Finally, different levels of yield advantage (and competition against weeds) were investigated: 0, +5, +10 and +20 percent over the TT-canola crop. Given the uncertainty of some biological parameters crucial to the performance of RR-canola, initial seed densities for ryegrass and radish as well as canola weed-free yield were further evaluated in the context of this study. A list of the uncertain parameters and their value ranges is shown in Table 2.

Table 2 Values of uncertain parameters used in the sensitivity analysis (model default values in bold).

Parameters	Zero Value	Minimum value	Standard value	Maximum value
Ryegrass initial seed density (seeds m^{-2})	0	100	**400**	1600
Radish initial seed density (seeds m^{-2})	0	25	**100**	400
Glyphosate control efficacy in-crop (%)		80	**95**	100
Canola weed-free yield (ton ha^{-1})			**0.9**	1.2
RR-canola yield advantage (%)	0	+5	**+10**	+20
RR-canola technology fee ($ ha^{-1})			**30**	50

The design of the complete factorial experiment involved the six parameters at the two, three or four parameter levels shown in Table 2. The sensitivity analysis for Scenario 1 and Scenario 2 amounted thus to 768 solutions (4^3 x 2^2 x 3). Scenario 3 was not submitted to this type of analysis.

RESULTS AND DISCUSSION

The summary results presented in Table 3 indicate excellent ryegrass and radish control in all scenarios and a long-term advantage of RR-canola over TT-canola. These results were obtained with all variable parameters set at their default levels (Table 2).

Table 3 Annuity and final weed densities for each scenario.

Scenarios	Annuity ($ ha^{-1} yr^{-1})	Ryegrass density (plants m^{-2})	Radish density (plants m^{-2})
Scenario 1 (RR-canola)	153	0	1
Scenario 2 (TT-canola)	142	0	2
Scenario 3 (TT-canola + pasture)	120	0	2

Weed densities

As shown in Table 3, weed numbers were generally kept low in all scenarios. The results conformed to the constraint imposed on the analysis that final seed numbers at the end of the last period could not exceed the starting seed numbers for year 1. Figures 1 and 2 further illustrate the changes in ryegrass and radish populations over time for Scenario 1 (RR-canola) and Scenario 2 (TT-canola). It can be seen that the rotation with TT-canola kept ryegrass under better control earlier in the period, partly as a result of using an application of a Group A herbicide in year 1 of this scenario (versus none in Scenario 1). Conversely, wild radish was controlled more effectively early in the period in the RR-canola scenario. This was due to one use of post-emergence glyphosate in the RR-canola phase, which killed 95 percent of the plants present (including the largest cohort of wild radish). For the rest of the period, other practices such as delayed seeding, harvest techniques or triazine applications in canola and lupins were responsible for the low weed numbers recorded for both ryegrass and radish in Scenario 2. Radish control late in the 20-year period was better in Scenario 1 as glyphosate in the RR-canola crop replaced the lost Group B herbicides.

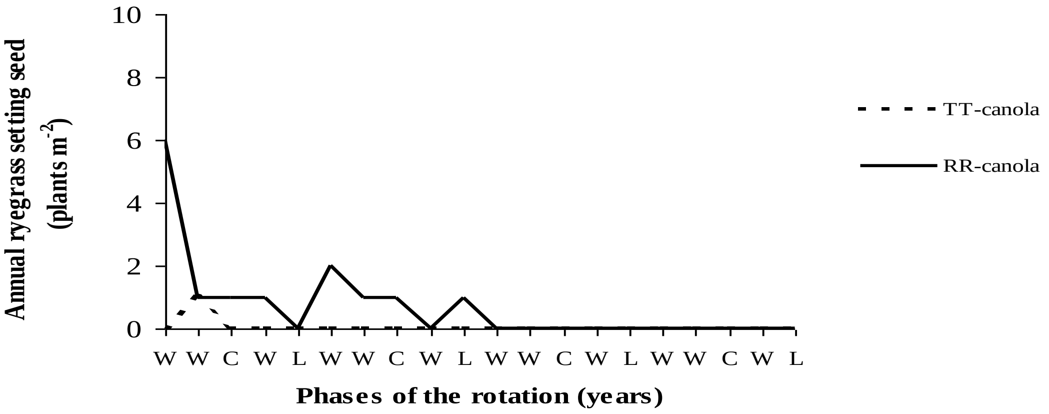

Figure 1 Density pattern of annual ryegrass over 20 years for a WWCWL rotation with RR-canola and the same rotation with TT-canola.

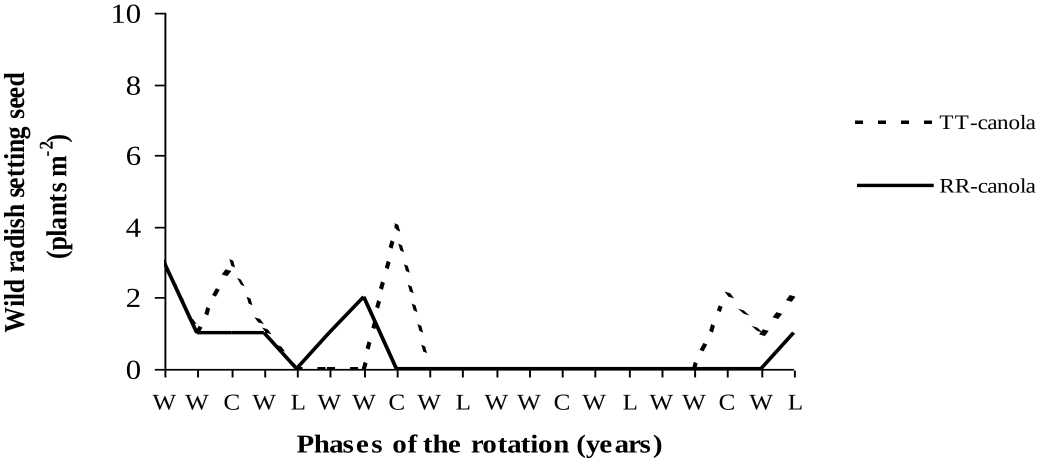

Figure 2 Density pattern of wild radish over 20 years for a WWCWL rotation with RR-canola and the same rotation with TT-canola.

Net value of RR-canola

The main result is that the long-term value of RR-canola was approximately \$11 ha^{-1} yr^{-1} higher than that of TT-canola grown in a similar cropping sequence (Table 3). Note that this profit advantage is an annuity over the whole 20 years, including all the different crops. The advantage in years when canola was grown would be greater, on average. Despite a default technology fee of \$30 ha^{-1} over the canola seed purchase cost, RR-canola appeared to perform better in terms of yield production, competition against weeds and opportunity for effective and inexpensive weed control. This is further illustrated in Figure 3, which shows the difference in enterprise gross margins between a WWCWL rotation with RR-canola and with TT-canola over 20 years. It is clear that the annual gross margin balance was nearly always positive in the sequence with RR-canola, the only exception being lupins in years 5 and 10 (-\$5 and -\$2 ha^{-1} yr^{-1}, respectively), due to the cost of extra simazine. RR-canola was always more profitable than TT-canola: by \$35, \$6, \$22 and \$3 ha^{-1} yr^{-1} in years 3, 8, 13 and 18, respectively. The differences mostly resulted from levels of weed density and choice of alternative weed control options. Given that up to two glyphosate applications were used in the RR-canola phases, less herbicide and non-herbicide treatments were required to control weeds in the wheat and lupins crops, increasing their annual gross margins by as much as \$25 ha^{-1} yr^{-1} in some cases. Generally, lupins presented low gross margins in both scenarios and wheat was particularly profitable after lupins due to the yield boost factor following a legume crop.

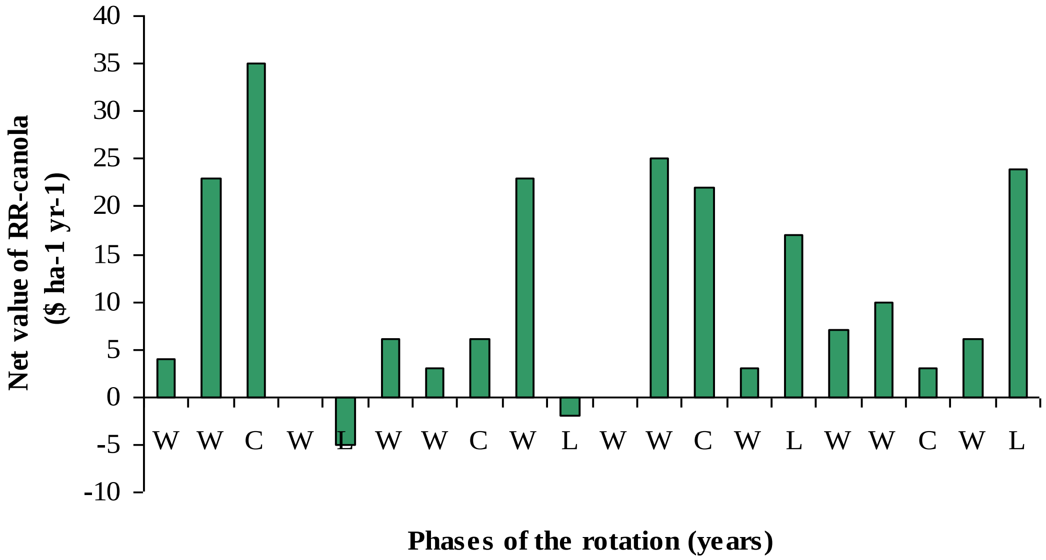

Figure 3 Difference in annual gross margins over the 20-year period between a WWCWL rotation with RR-canola and with TT-canola.

Results to this point have all been based on standard or “best bet” assumptions. Now consider the range of possible outcomes resulting in the different combinations of the parameters in the sensitivity analysis. If we assign probabilities to all of the scenarios modelled, and assume that they approximate the full range of possible outcomes, results can be presented as a probability distribution. For illustrative purposes, in constructing Figure 4 it is assumed that each of the 768 scenarios of the sensitivity analysis is equally likely.

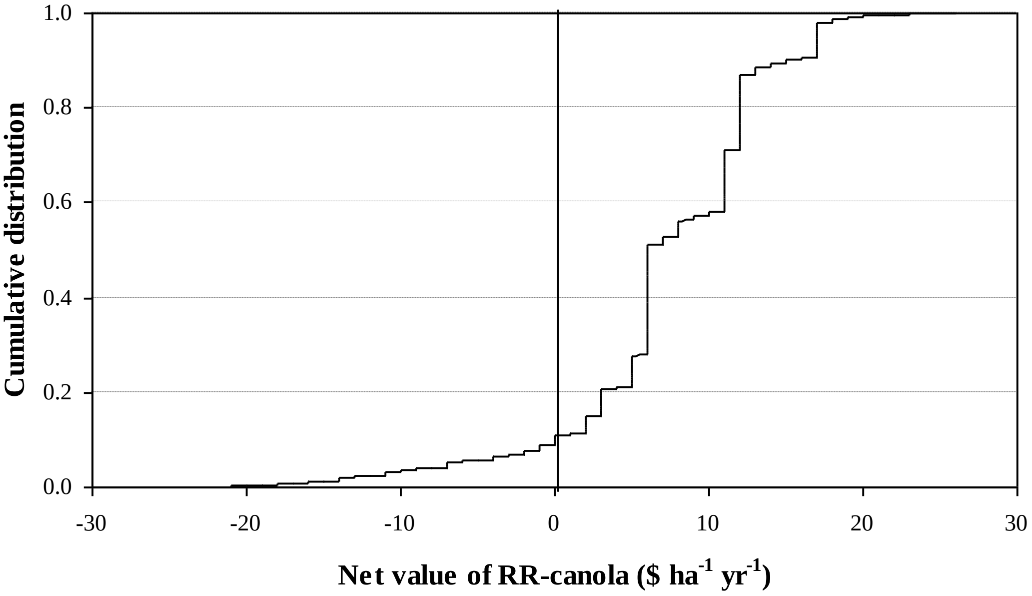

Figure 4 Cumulative distribution function for the net benefit of a RR-canola crop relative to TT-canola as part of a WWCWL rotation.

Figure 4 demonstrates that the net value of RR-canola was positive in 90 percent of the scenarios investigated in this analysis. Approximately 40 percent of scenarios had a net value greater than \$10 ha^{-1} yr^{-1}, with around half of the scenarios having values between \$0 and \$10 ha^{-1} yr^{-1}. The distribution mean is \$4.62 ha^{-1} yr^{-1} and the median is \$6 ha^{-1} yr^{-1}. This is lower than the “best bet” result, partly because the parameter ranges used were not symmetrical around the standard values.

The extent to which the value of a RR-canola crop was determined by the different uncertain parameters is discussed next.

Factors affecting the net value of RR-canola

Initial weed seed densities

Table 4 shows the effect of the different initial weed seed densities and the glyphosate efficacy in-crop on the net value of RR-canola, with all other variable parameters set at their default values.

According to the results presented, the attractiveness of RR-canola decreased, increased or remained unchanged as the weed numbers increased in the system. Such marked variability in results occurred because the value depended on how effective glyphosate was when applied post-emergence in RR-canola. At low glyphosate effectiveness (80 percent), an increase in ryegrass and radish numbers greatly decreased the value of RR-canola, particularly when ryegrass and radish densities were the highest. A maximum drop in the net benefit of RR-canola of \$23 ha^{-1} yr^{-1} was recorded between zero weed seeds m^{-2} and a combination of 1600 ryegrass and 400 radish seeds m^{-2}. Conversely, at 100 percent control efficacy of glyphosate, higher weed densities led to a consistently positive and increasing value of RR-canola (e.g. increase of \$10 ha^{-1} yr^{-1} in the net benefit between zero and maximum weed seed densities). When glyphosate was assumed to control 95 percent (default) of the ryegrass and radish plants or seeds, the value of RR-canola only increased by \$2 ha^{-1} yr^{-1} as weed densities increased from zero to their highest levels. This indicates that the RR-canola technology package needs to be highly effective in order for its use to be justified in the management of weed infestations.

Table 4 Net value of RR-canola ($\$$ ha^{-1} annuity over 20 years) as affected by glyphosate efficacy in-crop and initial weed seed densities.

Ryegrass seeds m^{-2}	Radish seeds m^{-2}	Glyphosate efficacy in-crop (%)		
		80	95	100
0	25	8	11	11
	100	3	11	12
	400	-8	11	15
100	0	9	11	12
	25	6	11	11
	100	1	11	13
	400	-9	11	16
400	0	4	11	13
	25	2	11	12
	100	-2	11	14
	400	-11	11	17
1600	0	-3	11	16
	25	-4	11	16
	100	-7	11	16
	400	-13	12	20

Glyphosate efficacy

As discussed before, the results shown in Table 4 clearly indicate that an increase in the level of weed control by glyphosate led to an increase in the overall profitability of the RR-canola rotation. Going from lowest to highest glyphosate efficacy, the increase in value of RR-canola was as high as $33 ha^{-1} yr^{-1} at high weed densities. This is logical, as the benefits of RR-canola technology rely very much on increased use of glyphosate.

Not only do the results of this analysis show that the farm profit would increase if a RR-canola crop was introduced in the system (with highly effective glyphosate in-crop), but a reduction in the usage of selective herbicides (Group A, in this case) would also be expected (Table 1). Conversely, higher use of glyphosate in a RR-canola system (six extra applications in this analysis) increases the risk of weeds developing resistance to this herbicide in the long run. Increased selection pressure on glyphosate is thus likely to reduce its availability to farmers over time (Lorraine-Colwill *et al.*, 1999). This was not modelled in the current analysis.

Canola yield

Table 5 shows how the net value of RR-canola was affected by canola yield (weed-free yield and yield advantage). All other parameters were assumed constant at their default levels.

Table 5 Net value of RR-canola (\$ ha^{-1} annuity over 20 years) as affected by canola weed-free yield and yield advantage.

Canola weed-free yield (ton ha^{-1})	Canola yield advantage (%)			
	0	+5	+10	+20
0.9	5	8	11	17
1.2	5	8	11	17

The results of Table 5 demonstrate that the weed-free yield of canola within the range modelled had no impact on the value of RR-canola, but an increase in the yield advantage of RR-canola over TT-canola by up to 20 percent increased its net value by up to \$17 ha^{-1} yr^{-1}.

Thus, the benefits of RR-canola result mainly from two aspects: 1) lower weed densities and 2) higher profitability of this type of crop. The higher profitability resulted from both the fact that cheaper control options could be used and also, quite importantly, the yield advantage of the new crop. Given that the net value of RR-canola was \$11 ha^{-1} yr^{-1} based on a default yield advantage of 10 percent, \$6 ha^{-1} yr^{-1} of that value was due to yield advantage and the remaining \$5 ha^{-1} yr^{-1} was due to good weed control. Such results confirm the idea that the introduction of transgenic crops could be a useful and profitable tool as part of an IWM program, given the extreme situation of herbicide resistance in the state of Western Australia.

Technology fee

As expected, the higher the technology fee, the lower the value of RR-canola in the rotation. The results in Table 6 show that, regardless of the crop yield, an increase of \$20 ha^{-1} in the technology fee led to a drop of \$5 ha^{-1} yr^{-1} in the value of RR-canola. Therefore, it is important to know the level of technology fee the producers of RR-canola are likely to impose on the buyers of this genetically modified crop seed when it is finally introduced in WA.

Table 6 Net value of RR-canola (\$ ha^{-1} annuity over 20 years) as affected by technology fee and canola yield.

Technology fee (\$ ha^{-1})	Canola weed-free yield (ton ha^{-1})	0.9				1.2			
	Yield advantage (%)	0	+5	+10	+20	0	+5	+10	+20
30		5	8	11	17	5	8	11	17
50		0	3	6	12	0	3	6	12

Proportion of canola in the rotation

Up to this point, the value of RR-canola has been investigated for a situation where the proportion of canola in the rotation is 20 percent (WWCWL). However, the value of RR-canola may increase if the proportion of this crop increases in the rotation. This issue was investigated for the following continuous cropping sequences with different proportions of canola:

a) WWCWLW with 16 percent of canola.
b) WCWL with 25 percent of canola.
c) WWC with 33 percent of canola.

A higher proportion of canola than 33 percent is not recommended as there is a substantial yield penalty when there is only one year between canola crops (assumed to be 50 percent). The 15 percent canola yield penalty assumed in the model when canola is only two years apart is considered acceptable, so the WWC sequence was included in the analysis.

Table 7 Annuities and net value of RR-canola at different proportions of canola in the rotation.

Annuities (\$ ha^{-1} yr^{-1})	Proportion of canola in the rotation (%)			
	16	20	25	33
Annuity of rotation with RR-canola	142	153	143	136
Annuity of rotation with TT-canola	135	142	130	117
Net value of RR-canola	**7**	**11**	**13**	**19**

Table 7 shows the net value of RR-canola (in bold) across rotations with different canola proportions. These results for the standard parameter values indicate that the net value of RR-canola increases as the proportion of canola in the rotation increases. This is mostly due to the higher profitability of RR-canola compared to TT-canola, but also in part because the risks of growing this crop (glyphosate herbicide resistance, gene flow) are not considered in this analysis. In addition, WWC (33 percent of canola) is the only sequence excluding lupins (a low profit crop), thus further increasing the overall profitability of the rotation.

The role of pasture

Table 3 showed that Scenario 3 was the least profitable of all, with an annuity of \$120 ha^{-1} yr^{-1} versus \$154 ha^{-1} yr^{-1} for Scenario 1 (RR-canola) and \$142 ha^{-1} yr^{-1} for Scenario 2 (TT-canola). This was mostly due to the lower profitability of pasture (at default outlook commodity prices), even though it provided excellent weed control. As illustrated in Figure 5, annual gross margins for pasture were relatively low (years 9 to 11), particularly in the year of pasture establishment (year 9), but subsequent crops were very profitable due to yield boost and low weed densities.

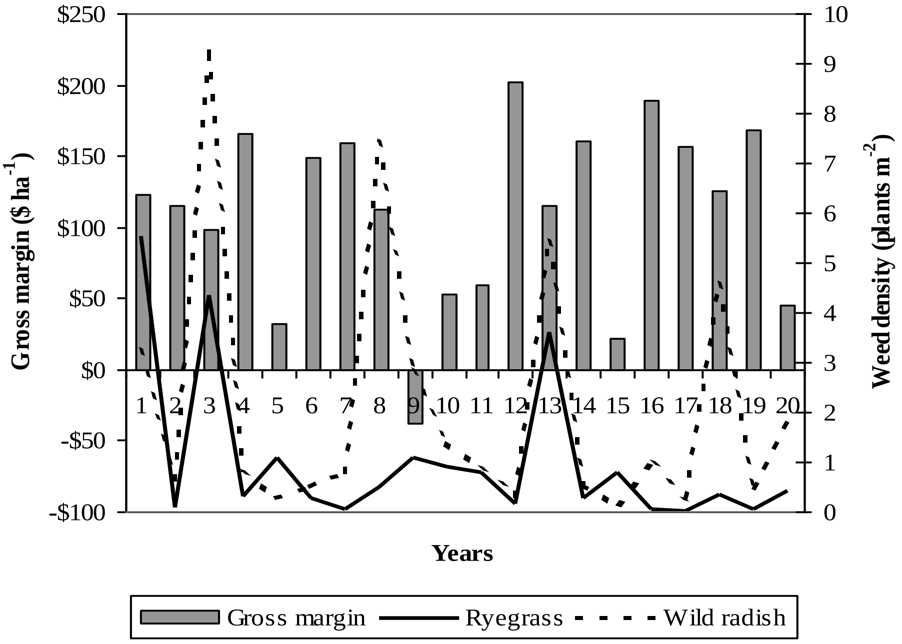

Figure 5 Annual gross margin (\$ ha^{-1} yr^{-1}) and weed density (plants m^{-2}) over 20 years for a WWCWL rotation (with TT-canola) punctuated with a 3-year phase of Cadiz serradella pasture in years 9-11 (Scenario3).

However, the value of pasture in the rotation may increase with higher sheep profitability. Sheep gross margins need to increase from \$11 to \$37 DSE^{-1} for the pasture rotation to break-even with the TT-canola scenario and by \$39 DSE^{-1} to break-even with the RR-canola scenario.

Table 1 shows that the advantage of including a pasture phase in the rotation with TT-canola is that it provided extra IWM tools for weed control, such as grazing and spray-topping to prevent seed set in spring. However, given that the number of glyphosate applications was kept relatively high (12) in this sequence, increased selection pressure on glyphosate is also expected to occur in the future (the choice between glyphosate and the other pasture spray-top herbicide represented in the model, paraquat, was made upon profitability). These results highlight the economic advantage (but higher risk) of using RR-canola rather than long pasture phases in the rotation as an alternative weed control tool.

CONCLUSIONS

The Multi-species RIM model was used to evaluate the value of including Roundup-Ready® canola (RR-canola, which has been genetically modified to become resistant to glyphosate (Roundup®) in place of triazine tolerant canola (TT-canola) in a typical Western Australian cropping system. The main conclusion is that the value of RR-canola is consistently higher than that of triazine-tolerant canola (TT-canola), currently dominating WA plantings. The results of this analysis indicate that the value of RR-canola is positive in 90 percent of all scenarios investigated (with approximately 40 percent of the scenarios resulting in a net value greater than \$10 ha^{-1} yr^{-1}). Since approximately one million hectares of canola are grown annually in Western Australia, the adoption of RR-canola would mean a substantial increase in farm profits in the state.

The benefits of RR-canola accrue from yield advantage of this crop relative to TT-canola (10-20 percent) and from cheap, effective weed control obtained with glyphosate. However, the results of this analysis indicate that the RR-canola technology package needs to be highly effective in order for its use to be justified in the management of ryegrass and radish infestations. The results further highlight the economic advantage (but higher risk) of using RR-canola rather than long pasture phases in the rotation as an alternative weed control tool. This situation would only change if livestock profits increased substantially (from \$11 to \$50 DSE^{-1}).

The economic results of this analysis show that it might be worth persisting with the introduction of RR-canola in Western Australia. Growing RR-canola will offer farmers greater flexibility in managing weeds and will likely prolong the life of selective herbicides.

Despite public debate on the risks of GM crops, the risks of gene flow from GM canola, of development of “super-weeds” and of problems with volunteer weeds have been found to be very low or negligible (GM Canola Technical Working Group, 2001). Furthermore, the impact of growing RR-canola on the environment is likely to be positive as a result of reduced usage of residual triazine in favour of safer glyphosate (GM Canola Technical Working Group, 2001). However, if RR-canola is widely adopted, there is a threat of increased evolution of resistance to glyphosate, thus reducing its availability to farmers over time. The sale of GM canola may also result in loss of international export markets (e.g. EU). The impact of GM canola products on human health is not expected to be significant as no traces of GM material are usually found in canola oil (GM Canola Technical Working Group, 2001). More risk assessment research is required in these areas.

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APPENDICES

Appendix 1 Parameters used in the multi-species yield-density equations.

Species 1	Species 2	Species 3	P_0	P_1	m	a	$k_{2.1}$	$k_{3.1}$	M
Wheat	Ryegrass	Radish	101	101-171	1.3	11	0.33	2.0	60%
Barley	Ryegrass	Radish	129	129-214	1.4	10	0.3	1.7	60%
Canola	Ryegrass	Radish	83	83-117	0.9	9.0	0.38	1.5	60%
Lupins	Ryegrass	Radish	40	40-66	1.0	7.0	0.25	1.5	70%
Ryegrass	Wheat	Radish	—	—	35,000	33	3.0	6.0	—
Ryegrass	Barley	Radish	—	—	35,000	33	3.3	6.0	—
Ryegrass	Canola	Radish	—	—	35,000	33	2.6	4.0	—
Ryegrass	Lupins	Radish	—	—	35,000	33	4.0	6.0	—
Radish	Wheat	Ryegrass	—	—	15,000	9.0	0.50	0.17	—
Radish	Barley	Ryegrass	—	—	15,000	9.0	0.60	0.17	—
Radish	Canola	Ryegrass	—	—	15,000	9.0	0.67	0.25	—
Radish	Lupins	Ryegrass	—	—	15,000	9.0	0.67	0.17	—

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

Biological variables	Ryegrass	Wild radish
Total % germination	82%	30%
% Germination of cohort 1 (prior to 1st chance to seed)*	5%	4%
% Germination of cohort 2 (1-10 days after break)*	38%	12%
% Germination of cohort 3 (11-20 days after break)*	23%	8%
% Germination of cohort 4 (before in-crop herbicides)*	14%	5%
% Germination of cohort 5 (after in-crop herbicides)*	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%

* Germination here refers to % of total initial seed bank, whereas in the RIM model these figures are scaled to give the % germination of seeds remaining in the seed bank.

Appendix 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, competing with crops sown at the opening rains, with a 10-day, or with a 20-day delay.

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

Appendix 4 Standard levels of weed control specified in Multi-species RIM. The values refer to the reduction in current wild radish plant or seed numbers for each control method.

Control methods	Wheat	Barley	Canola	Lupins	Volunteer pasture	Legume pasture
Knockdown option 1 - glyphosate (Group M)	99%	99%	99%	99%		99%
Knockdown option 2 - Spray.Seed® (Group L)	99%	99%	99%	99%		99%
2 knocks: glyphosate+Spray.Seed® (Gr M&L)	100%	100%	100%	100%		100%
Trifluralin (Group D)	70%	70%	70%	70%		
Simazine pre-emergence (Group C)			75%	75%		75%
Atrizine pre-emergence (Group C)			75%			
Glean® pre-emergence (Group B)	90%					
Logran® pre-emergence (Group B)	90%					
Use high crop seeding rate*						
Seed at first chance	5%	5%	5%	5%		5%
Tickle, wait 10 days, seed	5%	5%	5%	5%		5%
Tickle, wait 20 days, seed	5%	5%	5%	5%		5%
Simazine post-emergence (Group C)			75%	75%		
Atrazine post-emergence (Group C)			75%			
Glean® post-emergence (Group B)	90%	90%				
Logran® post-emergence (Group B)	98%	98%				
Eclipse® (Group B)	95%	95%		90%		
Broadstrike® (Group B)	90%	90%			90%	90%
Spinnaker (Group B)				95%	90%	90%
OnDuty® (Group B)			95%			
Lexone® + Brodal® (Group C+F)				98%		
Brodal® (Group F)				95%		
2,4-D Amine (Group I)	95%	95%			95%	95%
2,4-D Ester (Group I)	95%	95%				
Buctril MA® (Group C+I)	90%	90%				
Diuron + MCPA (Group C+I)	98%	98%				
Jaguar® (Group C+F)	98%	98%				
Tigrex® (Group I+F)	98%	98%			95%	95%
Affinity® + MCPA (Group G+I)	98%	98%				
Other selective herbicide	0%	0%	0%	0%	0%	0%
Grazing (selected automatically if pasture)**						
High intensity grazing winter/spring**						
Glyphosate top pasture (Group M)					85%	85%
Gramoxone® top lupins/pasture (Group L)				60%	65%	65%
Green manure	98%	98%	98%	98%	98%	98%
Cut for hay, then glyphosate (Group M)	95%	95%	95%	95%	95%	95%
Cut for silage, then glyphosate (Group M)	98%	98%	98%	98%	98%	98%
Swathe	35%	45%	35%	35%		
Mow pasture, then glyphosate (Group M)					98%	98%
User defined option A (Spring)	0%	0%	0%	0%	0%	0%
Seed catch - burn dumps	60%	60%	60%	60%		
Seed catch - total burn	68%	68%	68%	68%		
Windrow – burn windrow	30%	30%	30%	30%		
Windrow - total burn	40%	40%	40%	40%		
Burn crop stubble or pasture residues	20%	20%	20%	20%	20%	20%
User defined option B (at or after harvest)	0%	0%	0%	0%	0%	0%

* Effect of high seeding rate depends on weed and crop densities and on relative competitiveness of weeds and crops

** Effects of pasture differ for different pasture types and different lengths of pasture phases