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The economic value of glyphosate-resistant canola in the management of two widespread crop weeds in a Western Australian farming system

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Abstract

Multi-species RIM, a bio-economic model that simulates the population dynamics of two annual weed species over a 20-year period, was used to investigate the value of transgenic glyphosate-resistant canola in the management of herbicide resistant annual ryegrass and wild radish in a Western Australian dryland farming system. The perceived advantage of growing this crop is the potential to control post-emergent weeds with the broad-spectrum herbicide glyphosate, and without the yield penalty evident in triazine-resistant canola. We found that the economic value of glyphosate-resistant canola is consistently higher than that of the commonly grown triazine-resistant canola. However, the benefits of glyphosate-resistant canola would need to be weighed up against potential risks to marketability (due to consumer resistance) and risks of increased weed resistance to glyphosate (due to increased selection pressure).

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1. Introduction

Up to one million hectares of canola have been grown annually in Western Australia (WA). Control of weed species such as annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) is critical to achieving a viable canola harvest. Because both weeds are a major and extensive problem in WA, almost all of the canola grown in this state are triazine-resistant varieties due to a gene (selected by traditional breeding methods) endowing resistance to triazine herbicides (e.g. atrazine and simazine). Triazine herbicides provide selective control of annual ryegrass, wild radish and other weed species in triazine-resistant canola. However, the presence of the triazine-resistance gene results in a 10–20% crop yield penalty (and 2–3% lower oil content) relative to equivalent varieties that lack triazine resistance (reviewed by Holt and Thill, 1994; Moore and Carmody, 1997). In addition, the triazines are soil-active residual herbicides, with risks of carryover and damage to following cereal crops under low rainfall conditions (GM Canola Technical Working Group, 2001). In some countries, triazine herbicides are being phased out due to fears of groundwater contamination.

It is possible that transgenic canola varieties resistant to the broad-spectrum, otherwise non-selective herbicides glyphosate and glufosinate will be introduced to Australian agriculture. The perceived advantage is the potential to control many (post-emergent) weed species without the yield penalty inherent to triazine-resistant canola. This may also reduce reliance on, and thus help prolong the life of selective herbicides to which ryegrass and radish can be highly resistant (Llewellyn and Powles, 2001; Walsh et al., 2001). Therefore, the introduction of genetically modified glyphosate- or glufosinate-resistant canola may, other factors being equal, increase the options for weed control and the yield of canola crops. Conversely, increased usage of a herbicide to which the new crop is resistant can result in the evolution of weeds resistant to that herbicide. These trade-offs are discussed here.

This analysis investigates the use of genetically modified glyphosate-resistant canola (GR-canola) by taking a multi-species approach to evaluation of integrated weed management. It is assumed that glyphosate can be sprayed in-crop once or twice a year, and that GR-canola will have superior yield compared to triazine-resistant canola (TR-canola) (the default canola crop in the multi-species RIM model). However, genetically modified canola seed is likely to cost more than triazine-resistant genotypes due to a technology fee. Other issues associated with genetically modified crops (e.g. food quality, environmental impact, risks of gene flow and marketing), as discussed by Smith et al. (2000), are not considered in this study.

2. The multi-species RIM model

Multi-species RIM (Resistance and Integrated Management) is a farming systems bio-economic model that simulates the population dynamics and management of the two prominent crop weeds annual ryegrass and wild radish in WA, over a 20-year period. It is a decision support tool designed specifically for the evaluation of various management strategies to control ryegrass and wild radish in dryland agriculture. The model includes a detailed representation of the biology of ryegrass, wild radish, crops and pastures as well as of the economics of agricultural production and management (Monjardino et al., 2003). 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).

2.1. Ryegrass and wild radish biology

In multi-species RIM, weed seed production and expected crop yield after competition with the other species are calculated through the following general equation first proposed by Firbank and Watkinson (1985) and later modified by Maxwell et al. (1990), Diggle et al. (1994), and Monjardino (2002):

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

where Y is the weed seed production or proportion of grain yield after competition; m the maximum yield in the absence of competition; P_1 the density of species 1 (e.g. crop); P_2 the density of species 2 (e.g. ryegrass); P_3 the density of species 3 (e.g. wild radish); $k_{2.1}$ the competition factor of species 2 on species 1; $k_{3.1}$ 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).

Multipliers such as the maximum proportion of grain yield lost at very high weed densities and cohort structure are also included in the equation for crop yield and weed seed production, respectively. Only the general equation is shown here, but a more detailed description of the effect of weed-crop competition on the production of crop grain and weed seed can be found in Monjardino et al. (2003) and Pannell et al. (2004). Parameter values for Eq. (1) are shown in Table 1. Other key biological factors, such as seed germination, mortality and production (per cohort and according to time of sowing), which drive the pattern of weed population change over time are shown in Tables 2 and 3.

2.2. Enterprises

Multi-species RIM comprises a selection of seven different enterprises, including four crops: wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), canola or rape seed (*Brassica napus*) (assumed to be a triazine-tolerant variety) and lupins (*Lupinus angustifolius*); as well as three types of pasture for grazing by sheep: subterranean

Table 1
Parameters used in the multi-species yield-density equations

Species 1	Species 2	Species 3	P_1[a]	m[b]	a	$k_{2.1}$	$k_{3.1}$
Wheat	Ryegrass	Radish	101–171	1.3	11	0.33	2.0
Barley	Ryegrass	Radish	129–214	1.4	10	0.30	1.7
Canola	Ryegrass	Radish	83–117	0.9	9	0.38	1.5
Lupins	Ryegrass	Radish	40–66	1.0	7	0.25	1.5
Ryegrass	Wheat	Radish	–	35,000	33	3.00	6.00
Ryegrass	Barley	Radish	–	35,000	33	3.30	6.00
Ryegrass	Canola	Radish	–	35,000	33	2.60	4.00
Ryegrass	Lupins	Radish	–	35,000	33	4.00	6.00
Radish	Wheat	Ryegrass	–	15,000	9	0.50	0.17
Radish	Barley	Ryegrass	–	15,000	9	0.60	0.17
Radish	Canola	Ryegrass	–	15,000	9	0.67	0.25
Radish	Lupins	Ryegrass	–	15,000	9	0.67	0.17

[a] Plant density (plants m^{-2}) is only indicated for crops as weed densities vary over the course of the 20-year period.
[b] Maximum yield produced without competition is measured in ton ha^{-1} for crops and seeds m^{-2} for weeds.

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 (prior to 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 % of total initial seed bank.

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 pests or disease). Likewise, crop penalties can occur as a result of some control methods, for example by delaying crop sowing, by not swathing canola, 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;

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

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.

2.3. 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):

- 27 selective herbicides for grass and dicot weeds, which provide effective weed control, but result in a strong selection pressure for resistance when applied continuously (herbicides of high and moderate resistance risk) (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 (herbicides of low resistance risk).
- 17 non-herbicide methods, varying from cultivation and delayed sowing to 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.

Each control strategy has its own impact on weed mortality and seed set. However, Gill and Holmes (1997); Gorddard et al. (1996); Powles et al. (1997); Schmidt and Pannell (1996) suggest that no one method available provides the optimal management strategy for herbicide-resistant weeds. Instead, a combination of a wide range of weed control methods (i.e. integrated weed management or IWM) can achieve very effective and sustainable weed control. Because control methods are conducted at different times, their combined impacts are considered to be multiplicative rather than additive (Pannell et al., 2004).

Multi-species RIM 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).

2.4. 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 purchasing input; costs of operating machinery, maintenance and repayment; costs of contracting of labour for hay/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 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 (DSE), combining returns from wool and meat.

Because the model is run over 20 years, annual net profit must be discounted to make them comparable to the start of the period. A real discount rate of 5% per year is used for this purpose. The sum of discounted net profits or net present value (*NPV*) is shown in Eq. (2). In results presented later it is expressed in an annualized form on a per hectare basis (annuity)

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

where NPV is the net present value; TR the total return; TC the total costs; t the period considered (up to $T = 20$ years); and r is the real discount rate (5%).

The model does not optimize, 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.

3. Weed management scenarios

3.1. Enterprise sequences

The value of GR-canola was investigated by comparing three WA farming scenarios over 20 years:

- A continuous cropping rotation of wheat–wheat–canola–wheat–lupin (WWCWL) using GR-canola, which allows for extra applications of glyphosate in canola after crop emergence and before seed set (crop-topping).
- A continuous cropping rotation of wheat–wheat–canola–wheat–lupin (WWCWL) using TR-canola, with the traditional use of glyphosate before crop seeding.

- A wheat–wheat–canola–wheat–lupin rotation punctuated by a 3-year phase of French serradella pasture in years 9–11 (WWCWL + PPP). In this scenario the canola crop used was TR-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. In this system wheat is the main crop, with lupins and pasture included for their yield-boosting ability, and canola is commonly grown once in a 5-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.

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 in the field. The impact of different initial weed seed densities is investigated later in the paper. It was assumed that final seed numbers at the end of the simulation could not exceed the starting seed numbers.

3.2. Herbicide use

Because there is widespread resistance in WA to selective herbicides in ryegrass (Llewellyn and Powles, 2001) and wild radish (Walsh et al., 2001), herbicide usage is constrained. The herbicide resistance status of the weeds is dealt with in multi-species RIM through defining the expected number of applications of each herbicide group 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). Glyphosate belongs to Group M. Table 4 summarizes the strategies for each scenario.

No applications of Group A herbicides were used in Scenario 1 (GR-canola) and only one application was profitably used in each of Scenario 2 and Scenario 3 (TR-canola) (Table 4). Nearly all five Group B herbicide applications were exploited 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 GR-canola rotation, where no triazine herbicides are allowed in canola. Similar use of other moderate- and low-risk herbicides was observed across all scenarios, except for glyphosate, which had significantly higher use in GR-canola and pasture.

3.3. 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 4. In general, these strategies included practices such as high crop seeding rates and, in some years,

Table 4
Strategies and implications of using GR-canola versus TR-canola

Strategies	Scenario 1	Scenario 2	Scenario 3
Enterprise sequence	WWCWL	WWCWL	WWCWL + PPP
Canola genotype	GR-canola	TR-canola	TR-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 (0) • Windrowing (3)	• Tickle, delayed seeding 20 days (2) • High crop seeding rates (20) • Swathing (4) • Seed catching (2) • Windrowing (7)	• Tickle, delayed seeding 20 days (1) • High crop seeding rates (17) • Swathing (4) • Seed catching (3) • Windrowing (7) • Burning (1) • Grazing (1) • High intensity grazing (2)

The number of applications of each control method is shown in brackets.

a shallow cultivation followed by delayed crop seeding (mostly 20 days). During crop harvest, swathing of canola was always 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 TR-canola by GR-canola reduced the necessity to employ delayed crop seeding and harvest techniques for effective weed control.

These strategies were identified in a simulation process of trial and error (i.e. by searching for the best management combinations) and were selected on the basis of the optimal 20-year profit. For the purpose of this study, the term "optimal" is used to refer to the strategy that produces the highest long-term profit (annuity) from within the data set.

3.4. Modifications to the model

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

- Adding glyphosate for use post-emergence and before seed set in spring. Associated cost ($4.76 L^{-1}), rate (1 L ha^{-1}) and efficacy (95% kill) were also included.
- Including a GR-canola yield advantage relative to TR-canola (10%).
- Adding a technology fee to the standard canola seed price ($30 ha^{-1}).

Since these figures cannot be known ahead of the release of GR-canola, these parameters were subjected to a sensitivity analysis later in this paper.

4. Results and discussion

The summary results presented in Table 5 indicate excellent ryegrass and radish control in all scenarios and a long-term advantage of GR-canola over TR-canola. These results were obtained with all variable parameters set at their default levels for a medium/low-rainfall region (325–450 mm per annum) with sandy loam soils.

Table 5
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 (GR-canola)	153	<1	1
Scenario 2 (TR-canola)	142	<1	2
Scenario 3 (TR-canola + pasture)	120	<1	2

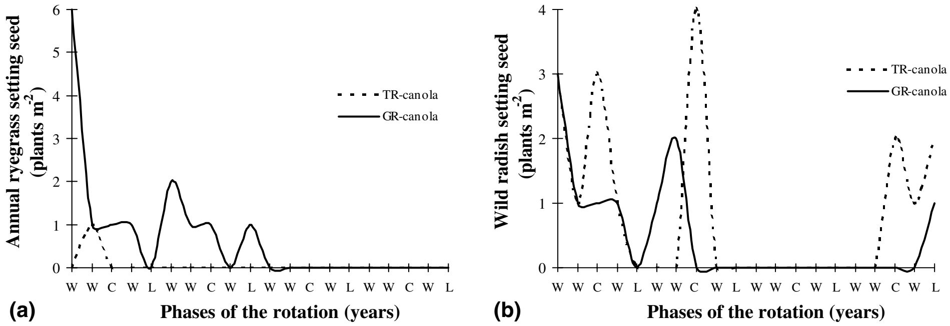

Fig. 1. Annual ryegrass densities (a) and wild radish densities (b) over 20 years for a wheat–wheat–canola–wheat–lupin rotation with glyphosate-resistant canola (GR-canola) and the same rotation with triazine-resistant canola (TR-canola) (W, wheat; C, canola; L, lupins).

4.1. Weed densities

As shown in Table 5, 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. Fig. 1 further illustrates the changes in ryegrass and radish populations over time for Scenario 1 (GR-canola) and Scenario 2 (TR-canola). Rotation with TR-canola kept ryegrass under better control earlier in the simulated 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 GR-canola scenario. This was due to one use of post-emergence glyphosate in the GR-canola phase, which killed 95% 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 GR-canola crop replaced the lost Group B herbicides.

4.2. Net value of GR-canola

The main result is that the long-term value of GR-canola was approximately \$11 ha^{-1} yr^{-1}higher than that of TR-canola grown in a similar cropping sequence (Table 5). 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, GR-canola is assumed to perform better in terms of yield production, competition against weeds and opportunity for effective and inexpensive weed control. This is further illustrated in Fig. 2, which shows the difference in enter-

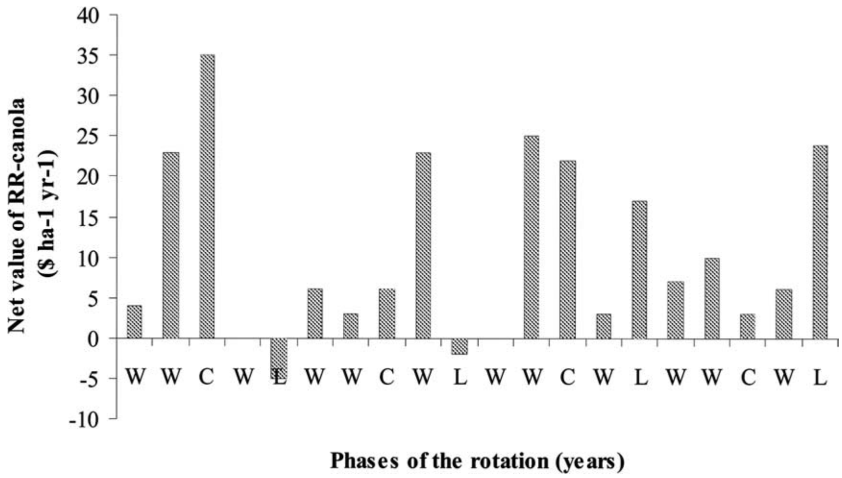

Fig. 2. Difference in annual gross margins over the 20-year period between a wheat–wheat–canola–wheat–lupin rotation with with glyphosate-resistant canola (GR-canola) and with triazine-resistant canola (TR-canola) (W, wheat; C, canola; L, lupins).

prise gross margins between a WWCWL rotation with GR-canola and with TR-canola over 20 years. It is clear that the annual gross margin balance was nearly always positive in the sequence with GR-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. GR-canola was always more profitable than TR-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 GR-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.

4.3. Sensitivity analysis

Sensitivity analysis was used to address parameter uncertainty and a list of the uncertain parameters and their value ranges is shown in Table 6 (left column for each level). Values of 80% and 100% reduction of ryegrass and radish plant/seed numbers were used to bracket the most likely range of weed control by glyphosate in-crop (Table 6). The flat technology fee added to the standard crop seed price was set at values of \$30 and \$50 ha^{-1} (estimates of likely market values). Finally, different levels of yield advantage (and competition against weeds) were investigated: 0%, +5%, +10% and +20% over the TR-canola crop. Given

Table 6
Values of uncertain parameters used in the sensitivity analysis (model default values in bold) and probability of occurrence for each parameter value (non-dimensional)

Parameters	Levels							
	Zero		Minimum		Standard		Maximum	
	Value	Prob.	Value	Prob.	Value	Prob.	Value	Prob.
Ryegrass initial seed density (seeds m^{-2})	0	0.05	100	0.2	**400**	0.5	1600	0.25
Radish initial seed density (seeds m^{-2})	0	0.05	25	0.2	**100**	0.5	400	0.25
Glyphosate control efficacy in-crop (%)			80	0.4	**95**	0.5	100	0.1
Canola weed-free yield (ton ha^{-1})					**0.9**	0.8	1.2	0.2
GR-canola yield advantage (%)	0	0.05	+5	0.15	**+10**	0.5	+20	0.3
GR-canola technology fee (\$ ha^{-1})					**30**	0.7	50	0.3

the uncertainty of some biological parameters crucial to the performance of GR-canola, initial seed densities for ryegrass and radish as well as canola weed-free yield were further evaluated in the context of this study. An indication of the impact of the crop sale price on the results is given by the inclusion of a technology fee.

The design of the complete factorial experiment involved the six parameters at the two, three or four parameter levels shown in Table 6. The sensitivity analysis for Scenario 1 and Scenario 2 thus amounted to 768 solutions ($4^3 \times 2^2 \times 3$). Scenario 3 was not submitted to this type of analysis.

Results to this point have all been based on standard or "best bet" assumptions. We 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 (Table 6, right column for each level), and assume that they approximate the full range of possible outcomes, results can be presented as a probability distribution (Fig. 3).

The net value of GR-canola was positive in 70% of the scenarios investigated in this analysis. Approximately 40% of the scenarios had a net value greater than \$10 ha^{-1} yr^{-1}(the mode is \$11 ha^{-1} yr^{-1}) with around 30% of the scenarios having values between \$0 and \$10 ha^{-1} yr^{-1}. The distribution mean is \$4.99 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.

Although a range of circumstances was investigated here, it cannot be concluded that these results apply across different farming systems. The extent to which the value of a GR-canola crop was determined by the different uncertain parameters is discussed next.

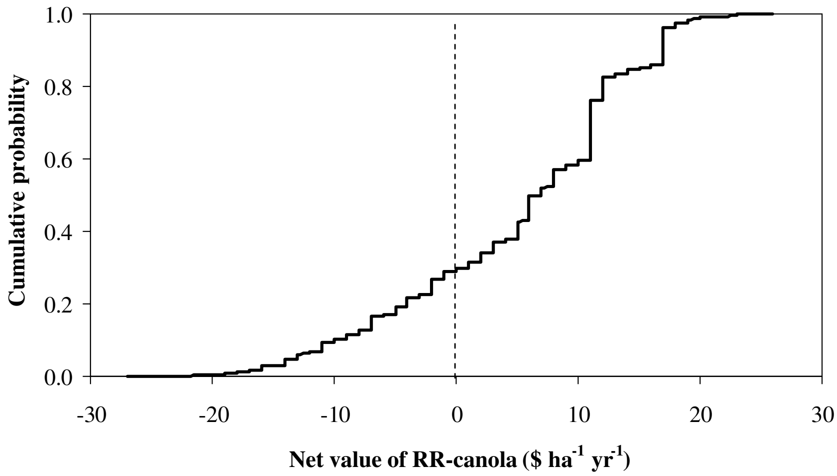

Fig. 3. Cumulative distribution function for the net benefit of a with glyphosate-resistant canola crop (GR-canola) relative to triazine-resistant canola (TR-canola) as part of a wheat–wheat–canola–wheat–lupin rotation.

4.4. Factors affecting the net value of GR-canola

4.4.1. Initial weed seed densities

Table 7 shows the effect of the different initial weed seed densities and the glyphosate efficacy in-crop on the net value of GR-canola, with all other variable parameters set at their default values.

According to the results presented, the attractiveness of GR-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 GR-canola. At low glyphosate effectiveness (80%), an increase in ryegrass and radish numbers greatly decreased the value of GR-canola, particularly when ryegrass and radish densities were the highest. A maximum drop in the net benefit of GR-canola of $21 ha^{-1} yr^{-1} was recorded between the lowest weed seed density and a combination of 1600 ryegrass and 400 radish seeds m^{-2}. Conversely, at 100% control efficacy of glyphosate, higher weed densities led to a consistently positive and increasing value of GR-canola (e.g. increase of $9 ha^{-1} yr^{-1} in the net benefit between low and maximum weed seed densities). The fact that the net value slightly dropped or remained unchanged at 25 radish seeds m^{-2} may be explained by a too low radish density to both cause major crop yield loss and compete effectively against ryegrass (and keep it under control), thus hardly justifying the use of GR-canola in that particular case. When glyphosate was assumed to control 95% (default) of the ryegrass and radish plants or seeds, the value of GR-canola only increased by $1 ha^{-1} yr^{-1}as weed densities increased from lowest to their highest levels. This indicates that the GR-canola technology package

Table 7
Net value ($ ha^{-1} yr^{-1}) of GR-canola as affected by glyphosate efficacy in-crop and initial weed seed densities

Ryegrass seeds m^{-2}[a]	Radish seeds m^{-2}[a]	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

[a] These numbers apply at the start of year 1. Later seed densities depend on the simulated seed dynamics.

needs to be highly effective in order for its use to be justified in the management of weed infestations.

4.5. Glyphosate efficacy

As discussed above, the results shown in Table 7 clearly indicate that an increase in the level of weed control by glyphosate led to an increase in the overall profitability of the GR-canola rotation. Going from lowest to highest glyphosate efficacy, the increase in value of GR-canola was as high as $33 ha^{-1} yr^{-1} at high weed densities. This is logical, as the benefits of GR-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 GR-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 4). Conversely, higher use of glyphosate in a GR-canola system (six extra applications in this analysis) increases the risk of weeds developing resistance to this herbicide in the long term (Neve et al., 2003a,b). Increased selection pressure on glyphosate is thus likely to increase resistance, and hence reduce its availability to farmers over time. Glyphosate resistance dynamics was not modelled in the current analysis (see Neve et al., 2003b).

Table 8
Net value ($ ha^{-1} yr^{-1}) of GR-canola as affected by technology fee, canola weed-free yield and yield advantage

Technology fee ($ ha^{-1})	Canola weed-free yield (ton ha^{-1}):	0.9				1.2			
	Canola 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

4.6. Canola yield

Table 8 shows how the net value of GR-canola was affected by canola yield (weed-free yield and yield advantage). All other parameters were assumed constant at their default levels.

The weed-free yield of canola within the range modelled had no impact on the value of GR-canola, but an increase in the yield advantage of GR-canola over TR-canola by up to 20% increased its net value by up to $12 ha^{-1} yr^{-1}.

Thus, the expected benefits of GR-canola result mainly from lower weed densities and higher profitability. The higher profitability resulted from both the fact that cheaper control options could be used and, importantly, the yield advantage of GR-canola over TR-canola. Given that the net value of GR-canola was $11 ha^{-1} yr^{-1} based on a default yield advantage of 10%, $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 indicate that the introduction of transgenic GR-canola could be a useful and profitable component of an integrated farming system in WA.

4.7. Technology fee

As expected, the higher the technology fee, the lower the value of GR-canola in the rotation. The results in Table 8 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 GR-canola. Therefore, the magnitude of the technology fee required from producers of GR-canola will be crucial to adoption of the technology.

4.8. Proportion of canola in the rotation

Up to this point, the value of GR-canola has been investigated for a situation where the proportion of canola in the rotation is 20% (WWCWL). However, the value of GR-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: WWCWLW with 16% of canola, WCWL with 25% of canola, WWC with 33% of canola.

A higher proportion of canola than 33% is not recommended as there is a substantial yield penalty (assumed to be 50%) due to fungal disease when there is only

Table 9
Annuities ($ ha^{-1} yr^{-1}) and net value ($ ha^{-1} yr^{-1}) of GR-canola at different proportions of canola in the rotation

	Proportion of canola in the rotation (%)			
	16	20	25	33
Annuity of rotation with GR-canola	142	153	143	136
Annuity of rotation with TR-canola	135	142	130	117
Net value of GR-canola	**7**	**11**	**13**	**19**

one year between canola crops. The 15% 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 9 shows the net value of GR-canola (in bold) across rotations with different canola proportions. These results for the default parameter values indicate that the net value of GR-canola increases as the proportion of canola in the rotation increases. This is mostly due to the higher profitability of GR-canola compared to TR-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% of canola) is the only sequence excluding lupins (a low profit crop), thus further increasing the overall profitability of the rotation.

4.9. The role of pasture

Table 5 showed that Scenario 3 was the least profitable of all, with an annuity of $120 ha^{-1} yr^{-1} versus $153 ha^{-1} yr^{-1} for Scenario 1 (GR-canola) and $142 ha^{-1} yr^{-1} for Scenario 2 (TR-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 Fig. 4, annual gross margins for pasture were relatively low (years 9–11), particularly in the year of pasture establishment (year 9), but subsequent crops were very profitable due to yield boost and low weed densities.

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

Table 4 shows that the advantage of including a pasture phase in the rotation with TR-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 based on profitability). These results highlight the economic advantage (but higher risk) of using GR-canola rather than long pasture phases in the rotation as an alternative weed control tool.

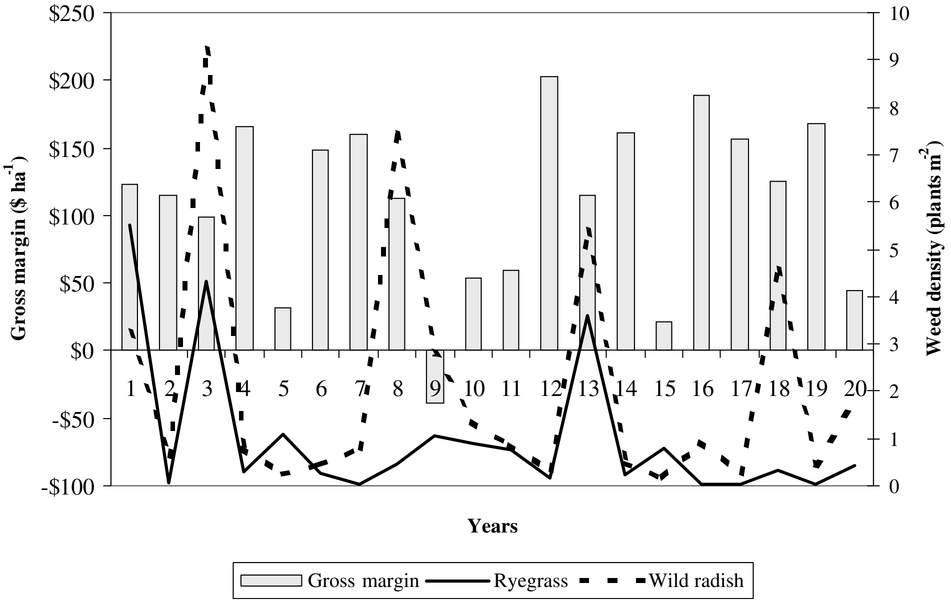

Fig. 4. Annual gross margin ($ ha^{-1} yr^{-1}) and weed density (plants m^{-2}) over 20 years for a wheat–wheat–canola–wheat–lupin rotation (with triazine-resistant canola) punctuated with a 3-year phase of French serradella pasture in years 9–11 (Scenario3).

5. Conclusion

The multi-species RIM model was used to evaluate the economic value of including glyphosate-resistant canola (GR-canola) in place of triazine-resistant canola (TR-canola) in a typical Western Australia cropping system. The main conclusion is that the value of GR-canola is consistently higher than that of TR-canola, which currently dominates WA plantings. The results of this analysis indicate that the value of GR-canola is positive in 70% of all scenarios investigated (with an economic advantage greater than $10 ha^{-1} yr^{-1} in approximately 40% of the scenarios). Since up to one million hectares of canola are grown annually in WA, the adoption of GR-canola could mean a substantial increase in farm profits in the state. This estimate would be higher if wild radish alone had been considered in the analysis and lower if the focus were on ryegrass (Monjardino, 2002). Therefore, this study confirms the value of using a multi-species approach for assessment of integrated weed management. Using a complex multi-species model significantly affected the estimated value of GR-canola, depending on the density and the species of weeds considered. In a multi-species situation (given the model's assumptions) the dominant weed species clearly drives the economics of the system. These findings have obvious implications for farmers, since they often try to manage more than one weed species, but have difficulty making good decisions given so many biological, economic, management, seasonal and time considerations. Results also have implications for research and extension activities, as analyses and recommendations that take a multi-species approach are likely to be much more credible and relevant to both the scientific and the agricultural communities.

The benefits of GR-canola accrue from the yield advantage relative to TR-canola (10–20%) and from the inexpensive, effective weed control obtained with glyphosate. However, the results of this analysis indicate that the GR-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 GR-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 \$39 DSE^{-1}).

The results of this analysis (for this particular farming system) indicate economic benefits from the introduction of GR-canola. Growing GR-canola will offer farmers greater flexibility in managing weeds and may prolong the life of selective herbicides. Despite public debate on the potential impacts of GM crops, the risks of gene flow from GR-canola (Rieger et al., 1999, 2001), of development of "super-weeds" and of problems with volunteer weeds (GM Canola Technical Working Group, 2001) have all been found to be very low or negligible. Furthermore, the impact of growing GR-canola on the environment is likely to be positive as a result of reduced usage of residual triazine hebicides in favour of safer glyphosate (GM Canola Technical Working Group, 2001). However, if GR-canola is widely adopted, there is a threat of increased evolution of resistance to glyphosate, thus reducing its profitability and availability to farmers over time (Neve et al., 2003a,b; Diggle et al., unpublished). The sale of GM canola may also result in loss of international export markets (e.g. to the 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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