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RIM: a bioeconomic model for integrated weed management of *Lolium rigidum* in Western Australia

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Abstract

The RIM (resistance and integrated management) model is presented. RIM represents a wide diversity of herbicide and non-herbicide options for management of Australia's most important crop weed, *Lolium rigidum*, in the context of the non-irrigated extensive farming system of southern Australia. Enterprise choices in the model include cereals, lupins, canola and three types of pastures for grazing by sheep. Users of RIM may specify the enterprise sequence and any feasible combination of the 35 weed treatment options each year over 10 or 20 years. Weed treatment options include selective herbicides (11), non-selective herbicides (5), non-chemical treatments (16) and user-defined treatments (3). The model represents weed and seed bank population dynamics, weed-crop competition, weed treatment impacts (including phytotoxicity), agronomic details, and financial details. Economic and biological model results are presented for scenarios with differing levels of availability of selective herbicides and different rotational sequences.

Keywords: Bioeconomic model; Herbicide resistance; Integrated weed management; *Lolium rigidum*; Weed population dynamics; Weed competition; Weed economics

1. Introduction

Since 1975, farmers in Australia's extensive dryland agricultural systems have come to rely heavily on herbicides for weed control (Sindel, 2000). However, during

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the 1990s, the phenomenon of herbicide resistance in prominent crop weeds has increased dramatically (Walsh et al., 2001; Llewellyn and Powles, 2001). Annual ryegrass (*Lolium rigidum*), which has long been the most economically important weed of crops in southern Australia (Pannell, 1990a,b; Abadi Ghadim and Pannell, 1991) is the world's most severe example of herbicide resistance. Across much of southern Australia annual ryegrass exhibits multiple herbicide resistance across different herbicide modes of action (as exemplified in Burnet et al., 1994, and reviewed in Preston and Powles, 2000). Multiple resistance occurs as a result of selection pressure from application of multiple herbicide groups, or through generic mechanisms bestowing "cross resistance" to a range of chemical types, including types which have not been applied to the weeds.

The consequence of multiple and cross resistance to many herbicides is that farmers are not able to maintain weed control by herbicides and are required to introduce alternative methods of weed control. The alternatives include a return to practices that had been minimised as a result of herbicide availability, as well as innovative new practices. They include systems that rely on ecological processes, physical weed control methods, and a reduced range of chemical herbicides of types that are less prone to resistance (Powles and Bowran, 2000). Thus, by necessity, many Australian farmers are adopting diverse combinations of weed control measures, consistent with the concept of "integrated weed management" (IWM).

However, farmers face a number of difficulties in their decision making about IWM strategies:

- The farmers are unfamiliar and inexperienced with a number of the control options;
- Strategies must be evaluated over the longer term, not just for a single year;
- The long-term impacts of multiple control options are difficult to predict;
- The impacts of individual treatments within an integrated strategy are difficult to interpret from field observations;
- Some strategies have indirect, as well as direct costs; and
- There is a vast number of possible combinations of treatments to be considered.

Given these difficulties, IWM seems a topic for which a computerised decision support system could be especially valuable to farmers and farm advisors. To date, decision support systems for weed management have focused primarily on herbicides and most have had a relatively short-term focus (e.g. Doyle, 1997). The resistance and integrated model (RIM), described below, is unusual in representing a comprehensive set of weed control treatments, including both herbicide and non-herbicide options, over a long time frame, and including an economics module.

This study adds to a relatively small literature on economic aspects of integrated weed management (e.g. Bennett et al., 1977) or herbicide resistance (Orson, 1999) or both (Goddard et al., 1995, 1996; Schmidt and Pannell, 1996). The last cited paper presented results from a specific application of an early version of RIM.

The objectives of this paper are to describe the RIM model for annual ryegrass management, to present its key assumptions and to illustrate its use in an analysis of the economic and agronomic impacts of herbicide resistance. The next section includes an overview of the model and its development, followed by a description of the various components of RIM, including biological, economic and agronomic components. The model is used to evaluate the implications of reducing herbicide availability for the selection of weed control practices and to assess the economic consequences of lower herbicide availability. Results from these analyses are presented and discussed.

2. Model description

2.1. Overview

Underlying RIM is a dynamic simulation model. The model is deterministic and integrates economic, biological and agronomic components. For economic aspects, the time step is annual. For biological processes, particularly weed population dynamics, seven periods of the year are defined (see below). The model is implemented in a spreadsheet program, Microsoft Excel®, using formulae and Visual Basic macros.

The model includes approximately 500 parameters (biological, agronomic and economic) that are adjustable by users. Specification of values for each of these parameters was a major task in the development of RIM. Sources of data and information were numerous and diverse. Economic parameters were obtained from an existing whole-farm economic model (Morrison et al., 1986; Kingwell and Pannell, 1987; Pannell, 1996), and updated from budget guides published for farmers. Parameters for control effectiveness of weed control options were estimated based on long-term field experiments designed to evaluate their effects (Bill Roy, pers. comm.) and from other field trials conducted by the state government agriculture agency, Department of Agriculture Western Australia. Parameters for weed competition functions were calibrated in cooperation with weed scientists in Agriculture Western Australia and the Western Australian Herbicide Resistance Initiative at the University of Western Australia to provide relationships consistent with field trial evidence.

RIM is a decision support system—it is designed to provide information and insights to farmers to help them in their long-term decision making about management of annual ryegrass. RIM allows the user to simulate many different combinations of weed control treatments and observe their predicted impacts on ryegrass populations, crop yields and economic outcomes.

RIM represents a single field. The user can specify whether or not the ryegrass population in the field is resistant to each herbicide group, or how many applications of herbicides from each group are available before resistance will develop. This implies a sudden loss of herbicide efficacy, which approximates the reality of herbicide resistance development by annual ryegrass in southern Australia (Tardif et al. 1993). A wide variety of non-herbicide weed treatment options is included, so that as herbicides are lost, the best substitute treatments can be identified.

The enterprise options available for users to select are wheat, barley, canola, lupins, ‘‘volunteer’’ pasture (consisting of a mixture of grasses, legumes and other species), subterranean clover pasture (*Trifolium subterrameum*), and cadiz seradella pasture (*Ornithopus sativus*). The user may select these in any agriculturally feasible sequence. There are inter-year impacts of one enterprise on another, depending on the sequence selected. For example, a cereal crop grown after a legume crop or pasture benefits from a higher yield and a reduced requirement for nitrogen fertilizer (Pannell, 1995a, 1998).

Details of assumptions and equations of the model are provided by Pluske et al. (2002). The following description provides a selection of key information about the model.

2.2. Biology

2.2.1. Weed population dynamics

In the simulation model the year is broken into seven periods:

1. First rains of the growing season which allow crop sowing
2. Seeding to 10 days later
3. 11–20 days after seeding
4. Up to time of post-emergence herbicide application (if selected)
5. Post-emergence spraying to mid spring
6. Mid spring to harvest, and
7. Harvest to opening rains of the next season.

Biologically, the model operates at the level of these time steps, rather than on a daily or weekly time step. This was judged a suitable compromise between detail and practicality, as we lack the evidence for a finer time step for most elements of the model. In addition, this approach has proven accessible and understandable for most farmers.

Weed numbers (m^{-2}) and weed seed numbers in the soil (m^{-2}) are recorded at the end of each of the periods. Factors influencing these results include the following.

- Initial weed seed density in the soil (by default, 500 seeds m^{-2}).
- The timing of weed seed germination relative to the crop. Later germinating weeds produce fewer seeds per plant. For example, for crops sown at the first opportunity after the opening rains, the competitiveness of late-emerging weeds was set as follows (expressed as a percentage of weeds emerging at the same time as the crop): emergence on days 1–10 = 100%, days 11–20 = 47%, between day 21 and application of post-emergence herbicides = 34%, after post-emergence herbicides = 10%.
- Natural mortality of weeds and seeds (seedlings 5%, dormant seeds during growing season 20%, seeds during summer 30%).
- Seed production per plant [see Eq. (2)].
- Impacts of weed and crop densities on seed production per plant [see Eq. (1)].

- The effectiveness of treatments to reduce weeds or seeds (see Table 2 below).

2.2.2. Competition between weeds and crops

The yield of a crop depends on the relative competitive abilities of that crop and of ryegrass, and the densities of each. The standard competition relationship for wheat yield as a function of ryegrass density is shown in Fig. 1. The function is illustrated for two wheat plant densities: 100 plants m^{-2} (typical of current farming practice) and 160 plants m^{-2}.

The functional form underlying this relationship is

$$Y = \frac{(P_0 + a)}{P_0} \times \frac{P_1}{a + P_1 + (k \times W)} \times M + (1 - M) \tag{1}$$

where Y is crop yield (as a proportion of the weed-free yield), P_0 is a standard crop density, P_1 is the actual crop density, W is the density of weeds surviving all treatments, M is the maximum proportion of grain yield lost at very high weed densities, a is a constant that depends on the crop, and k is a constant reflecting the competitiveness of the weed on the particular crop. For wheat in competition with annual ryegrass, the default values are as follows: $P_0 = 100$, $M = 0.60$ (based on results of Pannell, 1990a, 1995b; Pannell and Gill, 1994), $a = 5$, and $k = 0.33$. This competition function is similar to the widely used hyperbola of Cousens (1985) but is more flexible in that it allows representation of different crop densities.

The effect of competition by the crop on ryegrass seed set (R_{SET}) (seeds m^{-2}) is described by the following equation, adapted from Maxwell et al. (1990).

$$R_{SET} = \frac{R_{MS}}{b + W_H + (c \times D)} \times \frac{W_H}{W} \times s \tag{2}$$

where R_{MS} is the maximum ryegrass seed production (seeds m^{-2} year^{-1}), b is the ryegrass background competition factor (reflecting a base level of intra-species

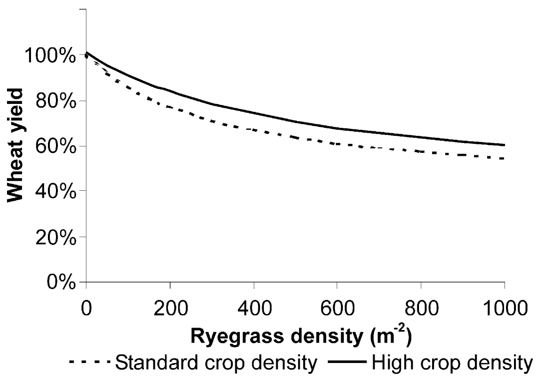

Fig. 1. Impact of weed competition on wheat yield. Densities illustrated are 100 (standard) and 160 plants m^{-2} (high).

competition affecting ryegrass seed production), c is the competition factor of crop on ryegrass, D represents density of crop (plants m^{-2}), W is the actual ryegrass density (plants m^{-2}) in early spring (i.e. the density of weeds surviving all treatments), W_H is the "healthy equivalent" ryegrass density (adjusted downward relative to W for later germinating weeds), and s is the sub-lethal effect of selective herbicides resulting in lower seed production of surviving weeds. Where wheat is grown, the assumed parameter values are: $R_{MS} = 35{,}000$, $b = 25$, $c = 3$, and $D = 100$ or 160 (depending on a management decision regarding seeding rate). W and W_H are calculated endogenously.

2.2.3. Crop-related variables

The following crop-related variables are represented.

- Standard weed-free yields for crops after a break of at least 3 years without a legume (1.3 tonne ha^{-1} for wheat).
- Yield boosts for cereals after legumes, canola or a pasture (e.g. 30% yield boost in first wheat after lupin crop).
- Yield effects on crops by green manuring and swathing (e.g. 10% boost in wheat after green manuring).
- Yield effects from disease in short rotations (e.g. 50% canola yield penalty if break between canolas is 1 year or 15% for a 2-year break).
- Seeding rates (e.g. 100 or 160 plants m^{-2} for wheat).
- Savings in nitrogen fertiliser following lupins and pasture (e.g. 30 kg ha^{-1} saving in first wheat after lupin crop).
- Impacts of delayed seeding on yield (see below).
- Parameters of the competition functions (see above).
- Phytotoxic effects of herbicides and some physical control measures on each crop (e.g. 3% yield loss in wheat treated with diclofop).

2.2.4. Pasture-related variables

RIM does not include detailed simulation of the population dynamics for each possible pasture species, so the biological impacts of a pasture phase on ryegrass populations are represented in a relatively simple way. For each type of pasture, the impact on ryegrass seed density under standard and high intensity grazing conditions is specified (Table 1) based on the advice of pasture scientists at the Department of Agriculture of Western Australia. The standard reduction in weed seeds is greater in a second or third consecutive year of pasture because the non-ryegrass components of the pasture stand are denser and more competitive at these stages.

2.2.5. Herbicide resistance

The herbicide options available in RIM are shown in Table 2. Each herbicide is allocated to a particular group, based on the mechanism by which it controls weeds. The groups are indicated in Table 2 (e.g. glyphosate is in Group M) using group names adopted as standards within Australia. All herbicides within a group are

Table 1
Reduction in number of ryegrass plants setting seed as a result of grazing

	Pasture type		
	Sub-clover	Cadiz serradella	Volunteer (mixed)
Standard grazing intensity			
First year of pasture	50	30	30
Second consecutive year of pasture	70	40	40
Third consecutive year of pasture	80	60	60
High grazing intensity			
First year of pasture	87	82	82
Second consecutive year of pasture	92	85	85
Third consecutive year of pasture	95	90	90

assumed to have the same resistance status. RIM does not simulate the population genetics of resistance development. Instead, the user can specify the number of applications available for each herbicide group prior to the onset of resistance. If ryegrass is fully resistant to a herbicide group, the limit for that group is set to zero. Given that the onset of high-level resistance is usually rapid and that the number of herbicide applications required to invoke resistance is reasonably predictable and well known, this simplified approach to representing resistance development in RIM is found to be effective for the types of management problems the model is used to address. It is also readily understandable and acceptable to farmers. Where an issue requires population genetics to be simulated explicitly, models other than RIM are available, although they lack many of RIM's other advantages. An example of such an issue is whether rotating between use of herbicides from different groups would increase the number of applications of either or both herbicide groups prior to resistance.

2.2.6. Treatment options

There are a total of 35 different weed treatment options included in RIM (Table 2). They can be broken into four separate groups: selective herbicides (11), non-selective herbicides (5), non-herbicide treatments (16) and user-defined treatments (3).

Non-herbicide treatments are based on physical or ecological approaches (although some also include an application of glyphosate to enhance their effectiveness). They include the following.

- Cultivation and delayed sowing: Cultivation is used to stimulate germination and traditionally was used to uproot and kill plants. A shallow cultivation or "early tickle" for higher germination is often used in Western Australia and is the cultivation method available in RIM. A delay between the tickle and seeding is necessary to allow the weeds to germinate. The longer the delay, the more weeds germinate, but at the cost of a crop yield penalty due to a shortened growing season. In RIM, sowing can be delayed by 10 days (wheat yield penalty = 5%) or 20 days (wheat yield penalty = 10%).

Table 2
Weed treatment options included in the RIM model

	Treatment	Type[a]	Kill percentage (in wheat crop, unless otherwise specified)
1	Knockdown option 1—glyphosate (Group M)	N	97
2	Knockdown option 2—paraquat/diquat (Spray.Seed®) (Group L)	N	97
3	2 knocks: glyphosate + paraquat/diquat (Spray.Seed®) (Groups M & L)	N	100
4	Trifluralin (Group D)	S	70
5	Simazine pre-emergence (Group C)	S	75 (canola)
6	Atrazine pre-emergence (Group C)	S	75 (canola)
7	Chlorsulfuron (Glean®) pre-emergence (Group B)	S	85
8	Use high crop seeding rate	B	See text
9	Seed at first chance (default)	B	5
10	Tickle, wait 10 days, seed	B	5
11	Tickle, wait 20 days, seed	B	5
12	Simazine post-emergence (Group C)	S	75
13	Atrazine post-emergence (Group C)	S	75
14	Chlorsulfuron (Glean®) post-emergence (Group B)	S	30
15	Diclofop (Hoegrass®) (Group A)	S	95
16	Fluazifop (Fusilade®) (Group A)	S	95 (canola)
17	Clethodim (Select®) (Group A)	S	95 (canola)
18	Other Dim for lupins or canola (Group A) (e.g. Sethoxydim)	S	90 (canola)
19	Other selective herbicide	S	User specified
20	Grazing	B	See Table 1
21	High intensity grazing winter/spring	B	See text
22	Glyphosate top pasture (Group M)	N	85 (pasture)
23	Paraquat (Gramoxone®) top lupins/pasture (Group L)	N	85 (pasture)
24	Green manure	B	98
25	Cut for hay, then glyphosate (Group M)	B	95
26	Cut for silage, then glyphosate (Group M)	B	98
27	Swathe	B	20 (canola)
28	Mow pasture, then glyphosate (Group M)	B	98 (pasture)
29	User defined option A (Spring)	B	User specified
30	Seed catch—burn dumps	B	60
31	Seed catch—total burn	B	68
32	Windrow—burn windrow	B	50
33	Windrow—total burn	B	63
34	Burn crop stubble or pasture residues	B	30
35	User defined option B (at or after harvest)	B	User specified

[a] N = Non-selective herbicide, S = Selective herbicide, B = “Biological” treatment (non chemical).

• Grazing: Sheep help to control ryegrass by eating ryegrass seed over the summer months and eating the ryegrass plants in the pasture. Ryegrass mortality depends on pasture type, length of the pasture phase, and grazing intensity (i.e. stocking rate), all of which are selected by the user. Standard assumptions about weed mortality from grazing were given in Table 1.

• Green manure: This involves the ploughing of a growing crop or pasture into the soil prior to the weeds setting seed. This is a very effective method of weed control, assumed to prevent 98 percent of ryegrass seed production. However, if a crop is not harvested, it involves a substantial sacrifice in revenue.

• Mowing: A mower is used to cut the tops off the weeds prior to them setting seed (potentially useful in pastures). This treatment plus a follow-up application of glyphosate is assumed to give 95 percent weed control.

• Cut for hay or silage: Like green manuring and mowing, cutting hay or silage relies on acting before the weeds set seed. Both options are specified in RIM with a follow-up glyphosate application. The assumed ryegrass kill rate is 95–98%.

• Swathing: This involves cutting the crop while still green and laying it on the ground. Once dry, it is harvested. Swathing can reduce harvest losses of grain, and help managing moisture content of barley grain. It also provides a modest reduction in ryegrass seed production by cutting off ryegrass plant heads before they set seed. RIM includes seed reductions of 25% for swathing of barley, and 20 percent for canola or lupins.

• Seed catching: It is estimated that 75% or more of the ryegrass present at harvest passes through the harvester. Around 5% of farmers are experimenting with seed catching equipment, which collects all the seed and chaff from the harvester's top sieve into a cart towed behind the harvester. In RIM the control rate of seed catching is set at 60–68%. The observed kill range in field trials is 40–80%.

• Burn crop stubble or pasture residues: This strategy involves burning the residues remaining after harvest or grazing. The effectiveness of the burn depends on the type of fuel and density of the fuel across the paddock. In RIM the standard kill rate for ryegrass seed from a burn is 30% following crops or 20% following pastures.

• Header trails: Instead of the residues being distributed over the width of the header path, it is possible to concentrate them in a band behind the harvester for more effective later burning. The assumed weed control rate from burning is then increased to 50–63%.

• High crop seeding rates: Increasing the density of wheat plants from 100 to 160 plants m^{-2} or of lupin plants from 40 to 66 plants m^{-2} provides increased competition against weeds (Barrett and Cambell, 1973; Medd et al., 1985; Lemerle et al., 1995; Tanji et al., 1997; Cousens and Mokhtari, 1998), increasing crop yield and reducing weed seed production.

Of the non-selective herbicide options, a relatively novel one that features in the scenario analyses presented later is paraquat applied post-anthesis to lupins. Paraquat can be sprayed late-season in lupins or pasture just before weed seeds mature (Powles and Matthews, 1996). If timed correctly this practice can result in a substantial reduction in seed production, with tolerable levels of crop damage (20% reduction in lupin yield is assumed). The standard reductions in weed seed production assumed in RIM are 80% in lupins and 85% in pasture, based on an observed range of 50–90% (Gill et al. 1994).

With the recent dramatic increase in herbicide resistance (e.g. Llewellyn and Powles, 2001), all of the above options are being examined by farmers in Western Australia. Some of the practices are already well established (e.g. cultivation and delayed sowing, grazing, burning), some are expanding in use (e.g. seed catching, header trails, swathing) and some are yet to be widely adopted (e.g. high crop seeding rates, green manuring, mowing, cutting a crop for hay or silage).

2.3. Economics

RIM allows users to examine the potential for long-term benefits from short-term economic sacrifices. The question of whether a preventative strategy is economic in the long term depends on a host of factors, including the cost of the strategy, its impact on weeds, prices of outputs and the initial weed seed density.

The standard approach used by economists and financial analysts to assess long-term investments involves "discounting", which allows all costs and benefits to be expressed in the equivalent of their present day value (Robison and Barry, 1996). The costs and benefits of all strategies of interest are discounted and summed to determine the net present value (NPV), and the preferred strategy is that with the highest NPV.

If the discount rate used is the bank interest rate (which is common practice), then this process is equivalent to identifying the strategy which would result in the highest bank balance at the end of the period (assuming that all income is deposited in the bank account and accumulates interest, and all costs are withdrawn from the bank account and reduce the amount of interest earned). This "final bank balance" approach is the method used in RIM, based by default on a nominal interest rate of 8%. Calculations of the final bank balance also take account of the following factors.

(a) Tax is paid on interest earned. The tax system is represented simply, because there is so much variability between farmers in their tax arrangements. RIM allows the user to specify a single marginal tax rate (by default, 21%), which should be the rate of tax that would be paid on any additional income earned above current income.
(b) The inflation rate on sale prices in agriculture has historically been lower than the inflation rate on input purchase prices. In RIM, the default settings for the inflation rates on crop product prices (1%) and sheep product prices (0.5%) are lower than the assumed inflation rate on input costs (3%).
(c) Yields increase over time. This is hard to predict, but over the long term is a very significant factor. In RIM the standard annual rate of yield increases is set to 1.0% for crops and 0.5% for sheep products (per hectare, not per sheep).

2.4. Limitations

RIM will not automatically calculate which strategy is "best". Users evaluate strategies using experimentation and "trial and error".

RIM does not represent year-to-year variation in weather, potential yield or herbicide performance. Yields in the model do vary from year to year due to the sequence of crops and pastures selected, the level of weed competition, and the effects of different weed control strategies. Climatic conditions do not rule out any of the treatment options. Users can self-impose constraints on the use of different treatments.

RIM represents only a single field. Some strategies may involve changes in machinery or livestock management that have impacts at the whole-farm level. Similarly, RIM makes particular assumptions about the way that investments in machinery are financed (repayments at a constant nominal rate over 8 years). Farmers may need to further consider whole-farm cash flow implications of strategies outside of RIM before making adoption decisions.

Although considerable effort has been expended on data collection, there are still areas where the available information could be strengthened. For example, it would be helpful to have better information on the benefits of some weed control methods, and aspects of weed population dynamics. A related issue is the variation in biological and economic parameters between farms. The values included in the standard version of RIM are representative of a typical farm in a region of Western Australia, but need adjusting for other farm types and for other regions. Users can readily alter the parameter values to suit their particular situation.

3. Scenarios modelled

We present two scenario analyses to illustrate the use of RIM to evaluate weed management alternatives. The first is an analysis of different levels of availability of a selective herbicide. Reduced availability of a herbicide might be for either of two reasons: (a) the herbicide has been used in the past, so that a smaller number of applications remains available before the onset of resistance, or (b) the farmer wishes to conserve applications of the herbicide for future periods. The scenario is simplified for illustrative purposes. It is based on the assumption that ACCase inhibiting herbicides (groups A and B from Table 2) are the only selective herbicides available. No constraints are placed on the use of non-selective herbicides or non-chemical treatments, other than those that are required agriculturally. The analysis examines different intensities of use of the selective herbicide, ranging from 10 uses over 10 years down to two uses. Many farmers in Western Australia who face reduced herbicide availability due to herbicide resistance would currently fall within this range, so this analysis is highly relevant to the question of how farmers at different stages of resistance development should adapt their management in order to maintain high profitability.

In the first analysis, the crop sequence is fixed as a lupin-wheat rotation. In the second analysis, herbicide availability is set at 10 applications over 10 years, but the rotational sequence is altered to examine two other continuous crop rotations (lupin–wheat–wheat and continuous wheat) and a rotation that includes two years of pasture (pasture–pasture–wheat–lupin–wheat). The objective is to compare the rotations in terms of their economic performance and weed management. The rotation that includes pasture is of particular interest, as inclusion of a pasture phase has been promoted by some scientists as a means of slowing the development of some forms of herbicide resistance. The analysis examines whether this advice is consistent with an objective of maximising profits

4. Results and discussion

4.1. Comparison of high and low herbicide strategies

For each level of availability of the selective herbicide (2, 4, 6, 8 and 10 applications in total over 10 years), Table 3 lists the set of treatments (additional to selective herbicides) that are most profitable to include, based on the criterion of maximising final bank balance after 10 years. These treatments were identified by a process of extensive experimentation with the model.

Included in the results are non-herbicide options of increasing crop seeding rates, seed catching at harvest, and shallow cultivation with delayed seeding, and the non-selective herbicide option of paraquat applied post-anthesis to lupins.

Table 3 indicates that, as herbicide availability increases, the optimal total number of weed treatments other than selective herbicides falls substantially and steadily. As herbicide usage increases from 2 to 10 applications over the 10-year period, the optimal number of additional treatments falls from 35 to 13. This reflects the relatively high effectiveness of selective herbicides. A combination of numerous non-selective treatments is used to replace them if they are not available.

Interestingly, RIM reveals that well-designed, economical strategies involving less reliance on selective herbicides result in almost the same average density of weeds as do herbicide-dominant strategies. Despite the lower efficacy of the alternative treatments, it is economical in the long run to combine treatments such that high control of weeds is achieved. This is consistent with survey results in Western Australia, which have found that weed densities in farmers' fields with herbicide resistance are, on average, no greater than in non-resistant paddocks (Llewellyn and Powles, 2001). Thus the economic difference between the scenarios is not primarily due to differences in weed densities, but to differences in treatment costs.

These economic differences are substantial. As selective herbicides become more available, the equivalent annual profit (annualised gross margin) increases from A\$64 to A\$93 ha^{-1}. The marginal value of an additional herbicide application reduces as total herbicide usage increases. For example, going from two to four applications increases profit by A\$12 ha^{-1} $year^{-1}$, while going from eight to 10 increases profit by only A\$2 ha^{-1} $year^{-1}$.

Underlying these results are biological simulation results for weed population dynamics and agricultural production over the 10-year period. Fig. 2 illustrates the pattern of ryegrass density and enterprise gross margin (A\$ ha^{-1} $year^{-1}$ undiscounted) over the 10 year period. There is one application of selective herbicide each year (as is also the case in each of the subsequent figures) and the rotation commences with lupins in year 1. Weed numbers are consistently low, except in the final year where it is economic to slightly relax the level of weed control because subsequent

Table 3
Consequence of restricting usage of selective herbicides over 10 years (assuming lupin–wheat rotation)

	Applications of selective herbicide				
	2	4	6	8	10
Profitable treatments (other than selective herbicide) forming part of the integrated strategies[a]	High crop seeding rates (10)	High crop seeding rates (10)	High crop seeding rates (10)	High crop seeding rates (10)	High crop seeding rates (6)
	Paraquat top lupins (5)	Paraquat top lupins (5)	Paraquat top lupins (4)	Paraquat top lupins (2)	Paraquat top lupins (1)
	Seed catching cart, burn dumps (10)	Seed catching cart, burn dumps (10)	Seed catching cart, burn dumps (10)	Seed catching cart, burn dumps (10)	Seed catching cart, burn dumps (10)
	Delay seeding 20 days and apply glyphosate (10)	Delay seeding 20 days and apply glyphosate (6)	Delay seeding 20 days and apply glyphosate (2)	Delay seeding 20 days and apply glyphosate (1)	
Total usage of non-selective treatments	35	31	26	23	13
Weed density surviving to set seed (10 year average m^{-2})	3	6	8	6	6
Equivalent annual profit ($/ha)	64	76	83	91	93

[a] The number of years in which this treatment was applied is shown in parenteses.

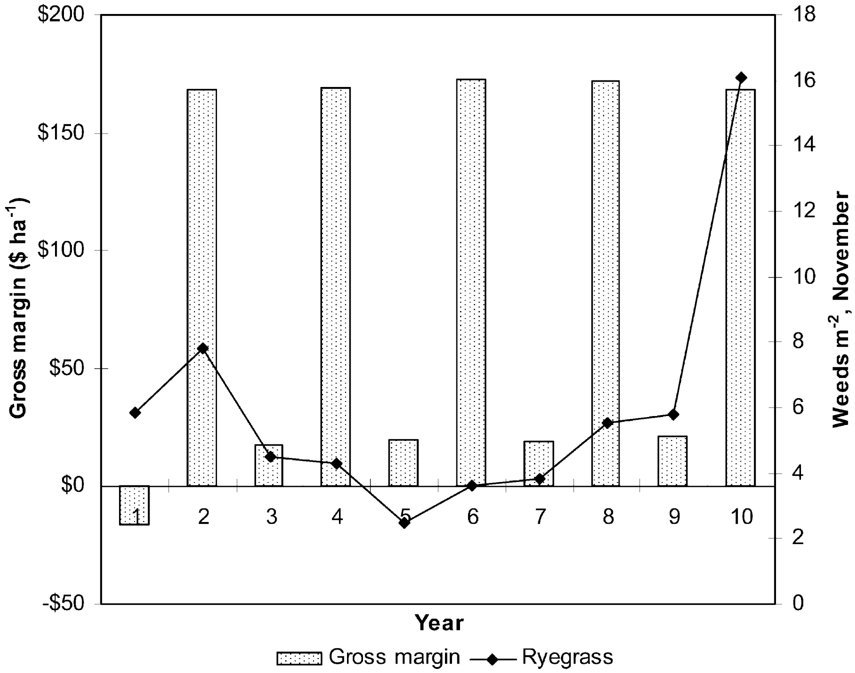

Fig. 2. Annual gross margin ($ ha^{-1}) and weed density in crop before harvest (m^{-2}) over 10 years for lupins:wheat rotation with 10 applications of selective herbicide subject to treatments shown in Table 3.

years are not included in the economic calculation. To limit the allowed extent of relaxation, a constraint is imposed that final weed seed numbers must not exceed numbers at the start of the first period.

For this rotation, gross margin oscillates from year to year, due to the low gross margin of the lupin crop. However, the gross margin in the wheat year is increased by the presence of lupins the previous years due to higher wheat yield and lower nitrogen fertilizer requirements. This is further apparent in the next set of results.

4.2. Interaction between rotation choice and weed management

Table 4 shows similar results to Table 3 but for a range of different crop and pasture rotation sequences. All are for the scenario of no more than 10 uses of selective herbicides. The results for the WL (wheat–lupin) rotation are the same as the final column of Table 3. They are included here for easy comparison.

The last rotation, which includes pasture phases, includes grazing as an additional weed control treatment. As Table 4 shows, the types of treatments selected for the first three cropping-only rotations are broadly similar, although high seeding rates are slightly less attractive in rotations with a greater frequency of wheat cropping. However, the rotation that includes pasture (pasture–pasture–wheat–lupins–wheat) is somewhat different in its mix of treatments. As well as high intensity grazing of

Table 4
Interaction between choice of crop–pasture rotation sequence and weed control practices over 10 years (assuming a maximum of 10 applications of selective herbicide)

Rotation:[a]	WL	WWL	WWW	PPWLW
Applications of selective herbicide:	10	10	10	6
Profitable treatments other than selective herbicide[b]	High crop seeding rates (6) Paraquat top lupins (1) Seed catching cart, burn dumps (6)	High crop seeding rates (3) Paraquat top lupins (1) Seed catching cart, burn dumps (7)	High crop seeding rates (2) Seed catching cart, burn dumps (7)	High crop seeding rates (6) Seed catching cart, burn dumps (2) Delay seeding 20 days and apply glyphosate (1) High intensity grazing of pasture (4) Paraquat top pasture (2)
Total usage of non-selective treatments	13	11	9	15
Weed density surviving to set seed (10 year average m^{-2})	6	5	10	11
Equivalent annual profit ($/ha)	93	102	102	70

[a] W = wheat, L = lupin crop, P = pasture (subterannean clover).
[b] The number of years in which this treatment was applied is shown in parentheses.

the pastures, paraquat is applied prior to weed seed set in the second of the two years of pasture. These treatments allow a lower reliance on seed catching, which is used only twice over the 10 years. Delayed seeding is used just once.

Most strikingly, the inclusion of these pasture phases with these weed treatments makes it not merely feasible but economically optimal to use fewer applications of selective herbicide. They are not used at all in any of the four pasture years. This means that the reported equivalent annual profit for pasture understates the true economic value of the strategy, since the figure of A\$70 ha^{-1} $year^{-1}$ does not include a value for the four applications of herbicide which have been conserved for future use. Judging from Table 3, these four applications might be worth between A\$10 and A\$20 ha^{-1} $year^{-1}$ (annualised) over the subsequent 10 years. Given the other assumptions about yields and sale prices underlying these runs, this extra value does not appear sufficient to make up the profit shortfall of the pasture rotation relative to the continuous cropping rotations.

Of the three cropping-only rotations, lupins–wheat–wheat and continuous wheat are similarly profitable. This reveals the contribution that lupins make to subsequent wheat profitability. In the lupins–wheat–wheat rotation, the contribution is sufficient to make up for the loss of income that occurs in the year of lupin production. Figs. 3

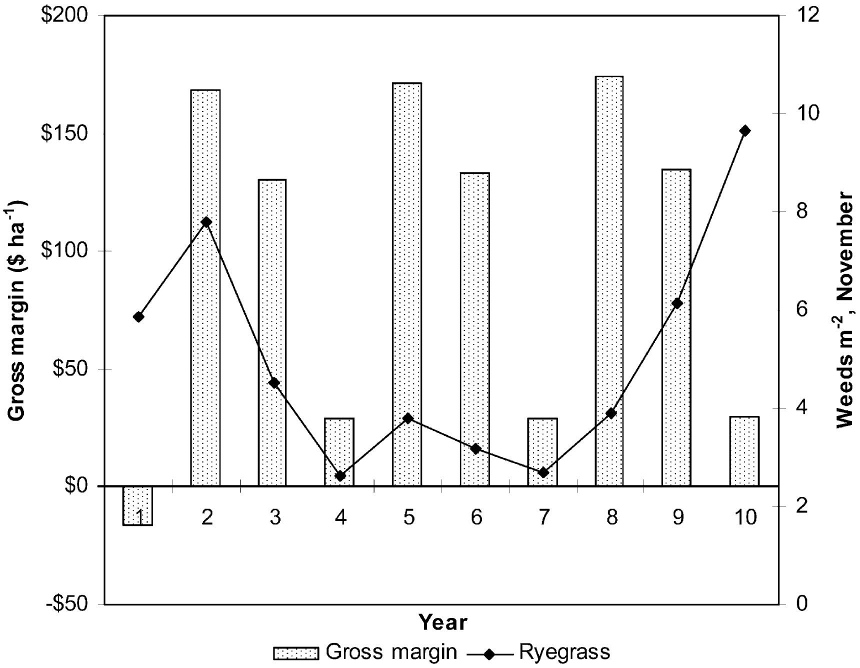

Fig. 3. Annual gross margin ($ ha^{-1}) and weed density in crop before harvest (m^{-2}) over 10 years for lupins:wheat:wheat rotation with 10 applications of selective herbicide subject to treatments shown in Table 4.

and 4 further illustrate this. In Fig. 3, the profitability is well above A$100 ha^{-1} year^{-1} in the wheat years, but low in lupin years (years 1, 4, 7 and 10). In Fig. 4, apart from the first 2 years when weed density is relatively high, wheat gross margin is approximately A$100 ha^{-1} year^{-1}. Average weed density is slightly lower in the lupin rotations than in the other two.

Finally, Fig. 5 shows the equivalent graph for the pasture–pasture–wheat–lupins–wheat rotation (commencing with the first year of pasture in year 1). Wheat is highly profitable each of the four times it is grown, as it follows a legume phase in each case. Weed numbers are relatively erratic, compared to other rotations, but little higher on average. The main reason for the lower profitability of this rotation is the assumed market prices for livestock outputs, rather than its biological productivity or effectiveness for weed management. A change in wool or meat markets could alter its economic performance. Nevertheless, the required increase in livestock prices for the profitability of this rotation to match that of the most profitable cropping rotation is high. RIM shows that sheep gross margin would need to increase from A$11 to A$29 head^{-1} year^{-1}. If an allowance of A$10 ha^{-1} year^{-1} is made for the average annual value of conserving four applications of selective herbicide, the required gross margin for sheep would be A$23 head^{-1} year^{-1}. Recently, meat prices have risen and gross margins for many farmers would currently exceed that threshold.

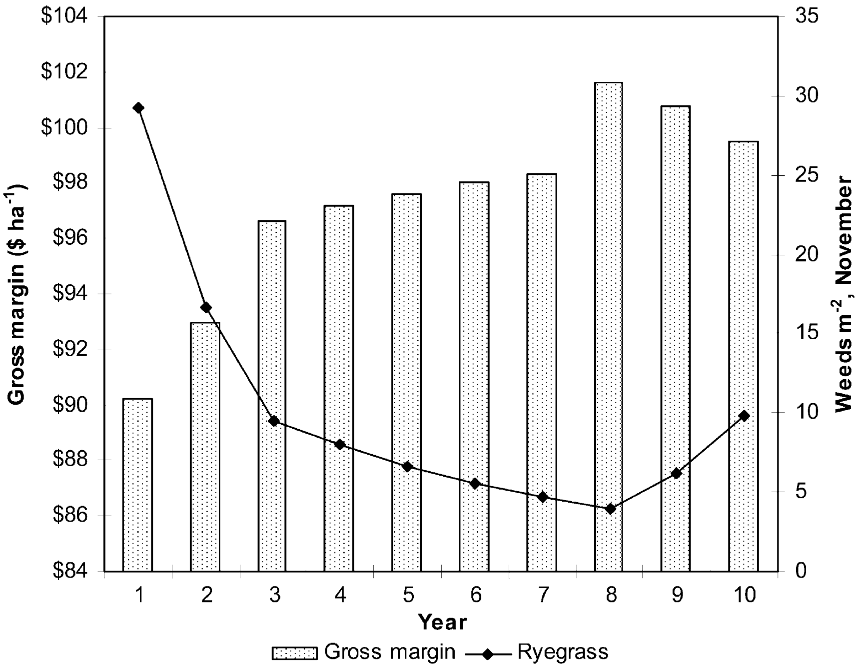

Fig. 4. Annual gross margin ($\$$ ha^{-1}) and weed density in crop before harvest (m^{-2}) over 10 years for continuous wheat cropping with 10 applications of selective herbicide subject to treatments shown in Table 4.

5. Uses and impacts of RIM

RIM is useful for a number of different types of users, including:

- farmers attempting to make decisions for their own weed management;
- private consultants, extension agents or agribusiness agronomists wishing to provide advice to their clients;
- facilitators running RIM with groups of farmers; and
- scientists, students and others wishing to understand the management of herbicide-resistant ryegrass.

Over 250 copies of the model have been sold, mainly in Western Australia. Anonymous surveys of farmers and farm-management consultants who have purchased RIM have revealed a high degree of satisfaction. The following quotes are selected from those surveys.

> Generally, I hold the program in very high regard.

> The number of times I mention the program [to farmer clients] would be in the hundreds.

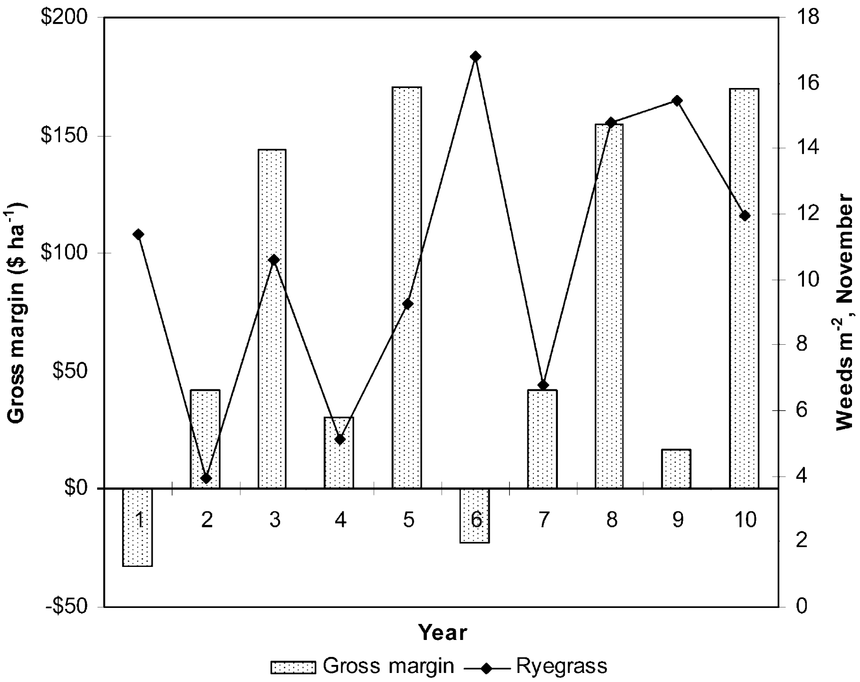

Fig. 5. Annual gross margin ($ ha^{-1}) and weed density in crop before harvest (m^{-2}) over 10 years for pasture:pasture:wheat:lupins:wheat rotation with 10 applications of selective herbicide subject to treatments shown in Table 4.

> It is a very good tool. All agronomists should use it to make farmers aware of this problem.

> Have found it a valuable management tool. Easy enough to use, and the results coming out of it are realistic enough to give it credibility.

A key method for delivering the model has been workshops with groups of farmers. The workshops include hands-on use of RIM by the farmers, group discussions and presentations by experts. A survey of 49 farmers who recently attended one of a series of these workshops in the Esperance region of Western Australia found the following.

- 38 out of 49 said that the workshop had changed their perceptions of some aspect of herbicide resistance management;
- 31 out of 49 said that they may change their crop-weed management as a result of attending the workshop;
- 39 out of 49 said that the RIM computer model is a useful tool for improving crop-weed management decisions;
- average ratings for “relevance of the workshop” and “value of attending the workshop” were 6 out of a possible 7.

Beyond these attitudinal surveys, Llewellyn et al. (2003) conducted a rigorous study of the impacts of attending a RIM workshop on the perceptions and management intentions of farmer attendees (compared to non-attendees). They found that attendance at a single workshop had statistically significant impacts on a number of perceptions and management intentions by the farmers.

6. Conclusion

RIM provides a powerful tool for evaluating the biological, agricultural and economic performance of alternative long-term weed management systems. The key difference that RIM makes is that it allows farmers to quickly examine many different combinations and sequences of management options, without needing to fear the consequences of mistakes. It also allows a first assessment of options about which they are not currently well-informed.

The model provides a comprehensive representation of the farming system at the single field level, complementing tools for whole-farm analysis by providing greater biological detail and a greater range of management options. It allows evaluation of important questions such as the following.

- How much income is likely to be lost by farmers once herbicide resistance develops?
- Which combination of strategies provides the best overall management system for a particular farming situation once resistance is present?
- Is it worth trying to delay the onset of resistance by using herbicides less frequently?
- Is it possible to maintain a continuous cropping rotation once resistance is present?
- If it is possible, is it economically sensible to maintain a continuous cropping rotation once resistance is present?
- If a pasture phase is included, how long should it be?
- Is a particular weed treatment a profitable practice? If so, in what circumstances?

In results presented it is shown that loss of herbicides due to herbicide resistance has severe economic ramifications in this farming system. As herbicides are progressively removed from the management system, a large number of alternative weed control practices are introduced. The economically preferred combination of these alternative practices is approximately as effective in weed control as the system including herbicides, but the cost of the herbicide-based system is substantially lower. Choice of crop-pasture rotational sequence is also shown to be an important tool for weed management. Inclusion of pasture phases has the potential to reduce reliance on herbicides, and it may be an economically attractive option depending on market prices.

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