Multi-species RIM: a bio-economic model for the integrated management of coexisting annual ryegrass and wild radish

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Summary A multi-species version of the bio-economic model Resistance and Integrated Management (RIM) was developed to deal with the complexities involved in the long-term integrated management of annual ryegrass (*Lolium rigidum* Gaud.) and wild radish (*Raphanus raphanistrum* L.). These two weed species dominate and co-exist throughout southern Australian dryland cropping regions. Here, we describe Multi-species RIM and demonstrate how the model can be used to evaluate weed management scenarios with differing levels of herbicide availability and different rotational sequences.

Keywords Multi-species RIM, annual ryegrass, wild radish, herbicide resistance, integrated weed management.

INTRODUCTION

Weed infestations in agriculture usually consist of a number of co-existing weed species In southern Australia, annual ryegrass (*Lolium rigidum* Gaud) and wild radish (*Raphanus raphanistrum* L.) frequently co-exist and are economically very important. The weed problem is dominated by these two species in very large areas (6 million hectares). Both weed species had been kept under control with selective herbicides; however, herbicide resistant populations are now widespread. Recent field surveys conducted throughout the wheatbelt of Western Australia indicated that approximately 70 and 20% of annual ryegrass and wild radish populations respectively, displayed herbicide resistance (Llewellyn and Powles 2001, Walsh *et al*. 2001). The situation is now such that farmers can no longer rely solely on selective herbicides for effective control of these species, but rather need to combine a range of herbicide and non-herbicide methods (integrated weed management, IWM) (Powles *et al*. 1997). The management of each weed species has been previously addressed in the single-weed versions of the model, Ryegrass RIM (Pannell *et al*. 2001) and Wild Radish RIM. (Monjardino *et al*. 2001). However, each species has its own requirements for control, making it difficult to manage these two weeds together. Hence, a multi-species version of the bio-economic RIM model was developed to aid in dealing with the complexities involved in the integrated management of annual ryegrass and wild radish over time.

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.

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:

$$Y = \frac{(P_0 + a)}{P_0} \times \frac{P_1}{a + P_1 + (k_{2.1} \times P_2) + (k_{3.1} \times P_3)} \times M + (1 - M) \quad (1)$$

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 (e.g. crop)
- P_2 = Density of species 2 (e.g. ryegrass)
- P_3 = Density of species 3 (e.g. 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.

Enterprises At present Multi-species RIM comprises a selection of seven different enterprises, including four crops (wheat, barley, canola and lupins), as well as three types of pasture for grazing by sheep (subclover, 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.

Weed control In the Multi-species RIM model there are 50 herbicide and non-herbicide control options available:

- 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 (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) suggests 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. The 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-herbicide 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:

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

Where:
NPV = Net present value
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.

RESULTS AND DISCUSSION

We now present and discuss a set of model results in order to illustrate the use of the Multi-species RIM to evaluate weed management scenarios. The first results show the implications of several rotational sequences with different crops/pasture, assuming the levels of availability of selective herbicides are held constant. In the second set of results, herbicide availability varies, while the enterprise sequence is unaltered.

Crop-pasture rotations Table 1 shows results for a range of crop and pasture rotational sequences. All are for the scenario of 10 applications of selective herbicides of high resistance risk (maximum of five applications for Groups A and B each). No constraints were placed on the use of non-selective herbicides or non-herbicide methods, other than those required agronomically. The first two rotations are continuous cropping based on wheat, with the last crop differing in each sequence (lupins and canola). The last rotation is a wheat-wheat-lupin sequence with a three-year Cadiz serradella pasture phase in years 9 to 11. Initial weed seed banks were assumed to be 200 annual ryegrass and 50 wild radish seeds m^{-2} in each case.

Weed control As Table 1 shows, all three rotations provide good weed control. The types of control methods selected for the first two cropping-only rotations were broadly similar, although practices like delayed

Table 1. Choice of crop/pasture rotation sequence and weed control practices over 20 years.

Rotation[A]	WWL	WWC	WWL+PPP
Application of Groups A&B	5A; 5B	5A; 5B	4A; 5B
Total usage of other herbicide	35	36	40
Profitable control options other than selective herbicides (No. of uses)[B]	• DS (1) • HSR (19) • Top (6) • Swath (3) • SC (11) • WR (6)	• DS (2) • HSR (19) • Top (0) • Swath (6) • SC (10) • WR (9)	• DS (0) • HSR (16) • Top (9) • Swath (0) • SC (10) • WR (3) • Burning (1) • Grazing (1) • HIG (2)
Weed density (20 y av. m^{-2})[C]	ARG = 1 WR = 0	ARG = 5 WR = 1	ARG = 3 WR = 1
Equiv. annual profit (\$ ha^{-1})	137	114	124

[A] W = wheat, L = lupin crop, C = canola, P = pasture (Cadiz serradella).
[B] DS = delayed seeding; HSR = high seeding rates; Top = crop/spray top; SC = seed catching; WR = windrowing; HIG= high intensity grazing.
[C] ARG = annual ryegrass; WR = wild radish.

seeding, swathing, seed catching and windrowing were slightly less attractive in the lupin rotation. This happened as a result of six profitable paraquat applications in the lupin phases, to minimise weed seed set. Conversely, atrazine was used on canola, but is not selective for use in lupins.

The rotation that included pasture was somewhat different in its mix of control options. The pasture phase allowed for grazing as an additional weed control method. Sheep help to control annual ryegrass and wild radish by grazing their seeds over the summer months and grazing vegetative plants during winter and spring. The Multi-species RIM model includes the option of high intensity grazing over the winter/spring period. The sheep are stocked at a sufficient intensity to minimise seed set. This option is economically preferred (compared to standard grazing intensity) in the last two years of the pasture phase, after establishment of the sward. In addition, a pasture phase allowed for a glyphosate application prior to weed seed set in every pasture year (pasture-topping), as well as burning of the pasture residues in the last year. These weed control practices allowed a lower reliance on other methods such as delayed seeding, use of high crop seeding rates and harvest techniques, all of which were used less often over the 20-year period. Finally, the inclusion of

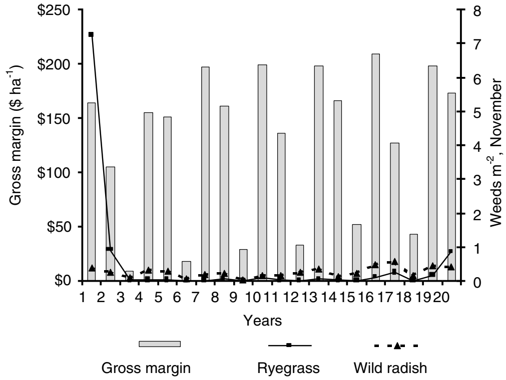

Figure 1. Annual gross margin (\$ ha^{-1}) and weed density in crop before harvest (m^{-2}) over 10 years for a wheat-wheat-lupin rotation with 10 applications of selective herbicides subject to control options shown in Table 1.

a pasture phase with these extra weed control options made it economically optimal to use fewer applications of selective herbicide (particularly of Group A-herbicides, which were used only four times over the entire period). No herbicides of Groups A and B were used in any of the three pasture years, but some Group B herbicides were more attractive in crops because they are effective on both ryegrass and wild radish.

Profit Of the two cropping-only rotations, wheat-wheat-lupins was the more profitable. Even though lupins are a less profitable crop than canola, they contribute more towards subsequent wheat profitability. In the model it is assumed that growing a lupin crop increases subsequent wheat yield by 30% in the first year and by 15% in the second year, due to the benefits of nitrogen fixation and several other factors. This contribution was sufficient to more than make up for the loss of income that occurred in the year of lupin production. Despite the model assumption that canola boosts wheat yield by 20% in the first year due to disease break, a 15% penalty is included for canola yield in this rotation as a result of a short two-year break in-between canola crops. Figure 1 further illustrates this for the lupin rotation. The gross margin of wheat is well above \$150 ha^{-1} y^{-1} in most wheat years (sometimes above \$200 ha^{-1} y^{-1}), but low in lupin years. In the canola rotation (graph not shown here), wheat gross margin is above \$100 ha^{-1} y^{-1} (never above \$180 ha^{-1} y^{-1}), but the average is \$70 ha^{-1} y^{-1} in canola years. Weed densities were similar across both rotations.

Finally, the main reason for the lower profitability of the pasture rotation (graph not shown here) compared to the WWL sequence is the lower assumed returns for livestock production, 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 sheep gross margin for the profitability of this rotation to match that of the most profitable cropping rotation is high. Multi-species RIM shows that it would need to increase from \$11 to \$26 DSE^{-1} $year^{-1}$.

Herbicide resistance status Table 2 shows the results of restricting usage of selective herbicides over a 20-year period. For illustration purposes, usage of selective herbicides of Groups A and B was reduced from five to zero applications each, i.e. to a scenario of full herbicide resistance. Note that only nine of the ten allowable uses of selective herbicides were included in the strategy, due to profit considerations. No constraints were placed on the other herbicide or non-herbicide control options (except those required for sound agronomy). The wheat-wheat-lupin rotation with a three-year Cadiz serradella pasture phase was used (the last sequence in the previous section).

For each level of herbicide availability, Table 2 lists the set of additional control options that are most profitable. It shows that, as herbicide availability decreased, the optimal total number of weed control options other than selective herbicides fell. As herbicide usage dropped from nine (maximum 10) to zero applications over the 20-year period, the optimal number of additional non-herbicide control options increased from 42 to 55. Usage of non-selective herbicides also increased slightly from 40 to 41. This reflects the relatively high effectiveness of selective herbicides. A combination of numerous non-selective practices is required to replace them when they are not available.

Multi-species RIM reveals that well-designed, economical strategies involving less reliance on selective herbicides may result in approximately the same average density of weeds as do herbicide-dominated strategies. Despite the lower efficacy of the alternative control options, it is economical in the long run to combine methods such that high control of weeds is achieved. This is supported by survey results in Western Australia, which found hardly any difference between ryegrass densities in fields with and without herbicide resistance (Llewellyn and Powles, 2001). Hence the economic difference between the scenarios is not due to differences in weed densities, but to differences in total weed control costs. These differences are shown in Table 2, where the equivalent annual profit decreased from \$124 ha^{-1} to \$120 ha^{-1} when selective herbicides became completely restricted.

Table 2. Consequence of restricting usage of selective herbicides over 20 years for a wheat-wheat-lupin rotation including a 3-year pasture phase in years 9–11.

Applications of Groups A and B	4A; 5B	0A; 0B
Total usage of other herbicides	40	41
Total usage of non-herbicides	42	55
Weed density (20 y av. m^{-2})[A]	ARG = 3 WR = 1	ARG = 2 WR = 0
Equiv. annual profit (\$ ha^{-1})	124	120

[A] ARG = annual ryegrass; WR = wild radish.

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REFERENCES

Llewellyn, R. and Powles, S. (2001). High levels of herbicide-resistance in rigid ryegrass (*Lolium rigidum*) in the wheatbelt of Western Australia. *Weed Technology* 15 (2), 242-248.

Monjardino, M., Pannell, D.J. and Powles, S.B. (2001). Wild Radish RIM: a bio-economic model for integrated management of *Raphanus raphanistrum* in Australian cropping. *Weed Research* (submitted).

Pannell, D.J., Stewart, V., Bennett, A., Monjardino, M., Schmidt, C. and Powles, S. (2001). RIM: a bio-economic model for integrated weed management. *Agricultural Systems* (submitted).

Powles, S.B., Preston, C., Bryan, I.B. and Jutsum, A.R. (1997). Herbicide resistance: impact and management. *Advances in Agronomy* 58, 57-98.

Walsh, M.J., Duane, R.D. and Powles, S.B. (2001). High frequency of chlorsulfuron resistant wild radish (*Raphanus raphanistrum* L.) populations across the Western Australian wheatbelt. *Weed Technology* 15 (2), 199-203.