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Managing Herbicide Resistance: Should you Conserve or Exploit your Herbicides?

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ABSTRACT

Herbicide resistance has become a major problem in dryland agriculture. In Australia this particularly applies to annual ryegrass (*Lolium rigidum*) which has developed multiple resistance to a wide range of commonly used selective herbicides. Although herbicides are a very cost-effective means of reducing weed density, major changes to their use are required if sustainable weed management is to be achieved. In this study a model of ryegrass population dynamics was used to identify the best integrated weed management strategies and to evaluate changes in the economic payoff when choosing to conserve herbicides rather than exploit them rapidly. A situation of evolving herbicide resistance was simulated for a continuous wheat-lupin rotation and two cropping sequences including one and two pasture phases. Conservation of the last four shots of the selective herbicide Hoegrass was found to be less profitable than their exploitation. Nevertheless, conservation provided a better long-term weed control. Benefits from conservation were lower in a situation of reduced level of weed control, but appeared to increase with the inclusion of more pasture in the rotation.

INTRODUCTION

Over the last decades herbicide resistance has become a serious problem in dryland agriculture. In Australia this situation has resulted from a widespread and profitable increase in herbicide use for weed control, adoption of minimum and no-tillage systems, and decline of pasture in favour of continuous cropping rotations. Repeated application of herbicides without the traditional weed control provided by cultivation and grazing has led to a high selection pressure on weed species. This particularly applies to annual ryegrass (*Lolium rigidum*) which, given its characteristics, has developed multiple resistance to a wide range of commonly used selective herbicides (Powles and Matthews, 1992; Gill *et al.*, 1994; Gill, 1997). Nevertheless, reliance on herbicides for weed control is expected to continue, because they are such cost-effective means of reducing weed density. However, it has been argued that major changes to current herbicide use patterns are required for sustainable weed management to be achieved (Powles *et al.*, 1998).

The purpose of this study is to find out whether farmers with an emerging problem of herbicide resistance are better off exploiting or conserving their remaining resources of selective herbicide. Our hypothesis was that conservation is more valuable in circumstances where weed density has greater potential to increase in the future. The model outlined below has been used to evaluate the complexity of the trade-offs involving these issues of weed management.

MODEL DESCRIPTION

RIM (Ryegrass Integrated Management) is a bio-economic model that simulates the dynamics of a ryegrass population over a 20 year period (Pannell *et al.*, 1998). It is a decision support tool designed specifically for the evaluation of various management strategies to control herbicide resistance in dryland agriculture. The model includes a detailed representation of the biology of weed, crops and pasture as well as of the economics of agricultural production and management.

Weed Biology

Growth and mortality of ryegrass weeds are represented in RIM according to the following equation based on Gorddard *et al.* (1996).

$$W = S G (1 - M_a) (1 - M_n) (1 - M_c) \quad (1)$$

Where

- W is density of weeds which survive to maturity
- S is seeds present at the beginning of a given year
- G is proportion of initial seed pool that germinates
- M_a is proportion of germinated seeds that die naturally over summer
- M_n is proportion of germinated seeds that are killed by non-chemical control
- M_c is proportion of germinated seeds that are killed by herbicide application

Seeds which remain dormant, hence do not germinate ($1 - G$), either die naturally or add to the following year's seed bank.

Enterprises

At present RIM comprises a limited selection of enterprises. They are wheat, lupins, and three types of pasture for grazing by sheep (clover, cadiz serradella and volunteer pasture). When any of these enterprises is chosen production of grain or wool occurs. However, crop production is reduced by competition with ryegrass, with the degree of yield loss positively related to the weed density (Maxwell *et al.*, 1990; Pannell, 1990). Moreover, some chemical treatments are assumed to affect potential crop yield as a result of phytotoxic damage by those herbicides applied in-crop (Schmidt and Pannell, 1996). Grain yield benefits provided by rotation with legumes are also accounted for.

Control Methods

In the model there is a wide range of chemical and non-chemical control options available.

- Selective herbicides provide a very effective weed control, but result in a strong selection pressure on weeds when applied continuously (Powles, 1997).
- Non-selective herbicides kill all plants by contact (including crops) when applied in sufficient doses (Gill *et al.*, 1994). Nevertheless, 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 very low.
- Non-chemical methods include anything other than using chemicals, varying from cultivation and delayed sowing to seed catching and stubble burning. Grazing during a pasture phase is another important option. Heavily weed-infested crops or pasture can be cut for hay/silage or used for green manure.

Each control strategy has its own impact on weed mortality and seed set, as shown in Table 1. However, Gorddard *et al.* (1996), Matthews (1996), Schmidt and Pannell (1996), Gill and Holmes (1997), and Powles *et al.* (1997) suggest that no one method available provides the optimal solution. Instead, only a combination of a wide range of weed control methods can achieve very effective weed control. Because control methods are conducted at different times, their combined impacts are considered to be multiplicative rather than additive (Bennett and Pannell, 1998)¹.

Table 1. Weed control methods and percent reduction in current ryegrass plants or seed numbers for some treatments used in the model (dashes signify that this treatment is not an option for this enterprise)

Treatment	Wheat	Lupins	Leg.Pasture
Hoegrass ®	95%	95%	—
Topping of lupins/pasture with Gramoxone ®	—	80%	85%
Tickle, wait 10 days, knockdown, seed	100%	100%	100%
Tickle, wait 20 days, 2x knockdown, seed	100%	100%	100%
Year-round grazing	—	—	*
High intensity grazing in winter/spring	—	—	**
Green manuring	90%	90%	98%
Cutting for hay	80%	80%	95%
Cutting for silage	85%	85%	98%
Mowing pasture	—	—	95%
Seed catching- burn dumps	60%	60%	—
Windrowing- burn windrows	50%	50%	—
Burning of stubbles and pasture residues	30%	30%	20%

* Ryegrass mortality under year-round grazing varies according to the phase of the pasture. For example, it is assumed that for Cadiz serradella it is 30% in the 1st year, 40% in the 2nd year and 60% in the 3rd year.

** Ryegrass mortality under high intensity grazing also varies according to the phase of the pasture. It is assumed that for Cadiz serradella it is 82% in the 1st year, 85% in the 2nd year and 90% in the 3rd year.

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

Economic Values

Costs, revenues, profit and net present value are calculated by the model. 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. Environmental costs associated with some non-chemical methods such as cultivation and burning are also represented in the model to some extent. Economic returns from crops and stock are based on grain and wool sale prices. Sheep value is given as a gross margin per DSE.

Following Gorddard *et al.* (1996), annual net profit from cropping one hectare is given by

$$R = P_w Y - C_n - C_h - C_f \quad (2)$$

Where

R	annual net profit
P_w	crop sale price
Y	crop yield
C_n	cost of non-chemical control
C_h	cost of herbicides
C_f	fixed costs (fertilisers, transport)

Because the model is run over 20 years time (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 gives the net present value (NPV).

$$NPV = \sum_{t=1}^T (P_w Y_t - C_{nt} - C_{ht} - C_{ft}) / (1 + r)^t \quad (3)$$

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.

Model Limitations

RIM is a deterministic model, meaning that it does not represent the year-to-year variation in growth, herbicide performance, prices or other variables (Dorr and Pannell, 1992). Instead, it is assumed that all years are identical in terms of their potential production, although the weed population varies over time and affects yield accordingly (Bennett and Pannell, 1998). It is not an optimisation model. Rather, optimal strategies for different scenarios are identified by extensive simulation of many strategies. Furthermore, neither pasture dynamics nor sheep behaviour are represented in the model. And all weeds other than ryegrass are assumed to be adequately controlled. There are also limitations regarding some data and estimated

parameters used in the model. They are based on experimental data where possible, but a number have had to be estimated subjectively.

RESULTS AND DISCUSSION

Control Strategies

The model is run over 20 years. Three sequences of enterprises were examined:

1. a continuous cropping wheat/wheat/lupin rotation,
2. a wheat/wheat/lupin rotation punctuated by a 3-year phase of cadiz serradella pasture in years 13-15.
3. a wheat/wheat/lupin rotation punctuated by two 3-year phases of cadiz serradella pasture in years 6-8 and 16-18.

The pasture phases are investigated because they allow high levels of weed control without the use of selective herbicides, and this may be desirable after resistance has fully developed or to delay build up of weed numbers without having to use up the available herbicide uses.

In all situations it was assumed that there were only four uses of the selective herbicide Hoegrass left available before complete herbicide resistance developed. The simplifying assumption was made that after four uses, resistance appears suddenly and completely. Although this is not always strictly accurate, resistance does frequently go from low levels to virtually the whole population in a period as short as three or four years (after several years of herbicide use) (Tardiff *et al.*, 1993; Powles *et al.*, 1997).

In the first scenario of herbicide exploitation the four herbicide “shots” were used up at the earliest opportunity. In the second scenario of herbicide conservation, the four shots of chemical were spread out over the whole 20-year period, instead of being used up all at the start. They were targeted towards years when the weed density was getting high.

To complement these strategies of herbicide application, many combinations of other control methods (non-chemical and non-selective herbicides) were investigated in order to find the most profitable integrated strategies of weed management. In general, these strategies included high crop seeding rates and, in some years, delayed times of sowing for crops and pasture. The use of delayed sowing was restricted to 10 days in a first year of a wheat phase and 20 days in the second year of a wheat phase when Hoegrass was not used. When applying the herbicide, the first wheat was sown at the first opportunity and the second wheat was sown 10 days after the break of the season. Sowing was not delayed for lupins at all, consistent with usual farmer practice. Lupin crop-topping and pasture spray-topping with the non-selective herbicide Gramoxone (only in the last two years of each pasture phase) proved to be profitable practices in the long run. Sustainable grazing is recommended during the first year of pasture for good pasture establishment (Nutt and Paterson, 1997), but the last two years were grazed intensively in spring and early winter to obtain good weed control. Seed catching combined with burning of dumps was always the most

attractive control method during crop harvest. Pasture residues were burnt during the last year of each pasture phase, previous to cropping. However, an effective burn can only be obtained where sufficient dry pasture residues are maintained (Reeves and Smith, 1975).

Weed Density

Table 2 shows the NPVs and finishing weed densities for the various scenarios. Figures 1, 2 and 3 show weed densities over the full 20-year period.

Table 2. Effect of herbicide exploitation and conservation on NPV per hectare and weed density under three different enterprise sequences. The net value of conservation is also represented

	Continuous Cropping		1 Pasture Phase		2 Pasture Phases	
	NPV (\$/ha)	Weeds setting seed ^A	NPV (\$/ha)	Weeds setting seed ^A	NPV (\$/ha)	Weeds setting seed ^A
Herbicide Exploitation	121	755	127	516	116	109
Herbicide Conservation	111	110	124	152	119	25
Net value of Conservation	-10		-3		3	

^AAverage over the last three years.

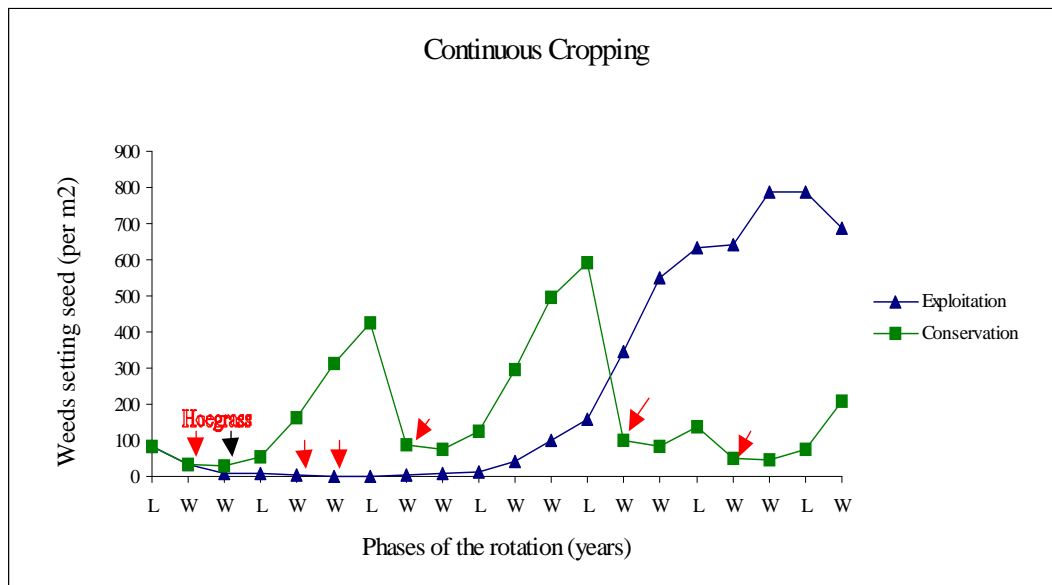


Figure 1. Weed density in each of the 20 years of a continuous cropping rotation (W- wheat, L- lupins)

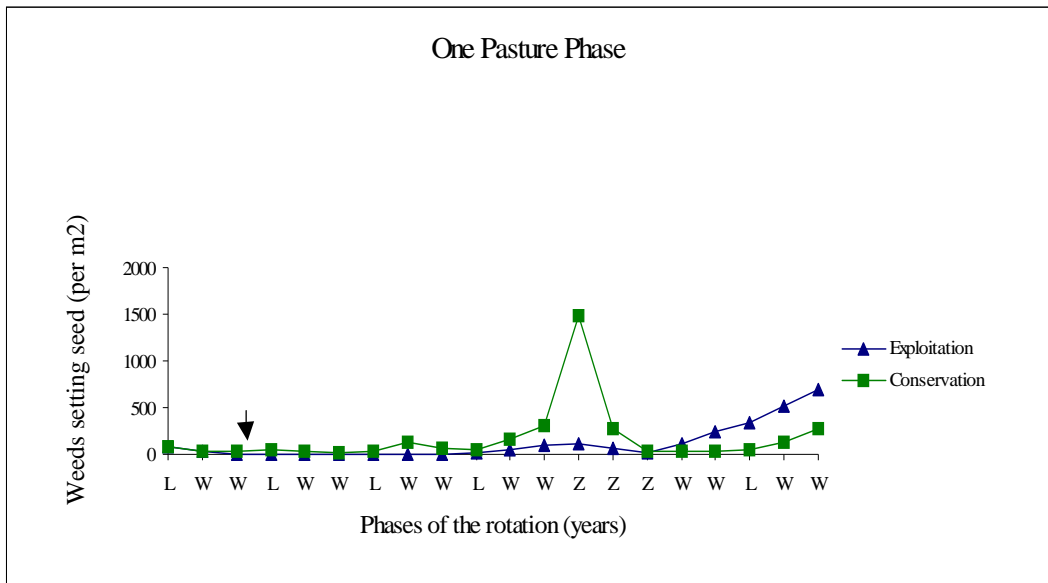


Figure 2. Weed density in each of the 20 years of a cropping sequence with one pasture phase (W- wheat, L- lupins, Z- cadiz serradella pasture)

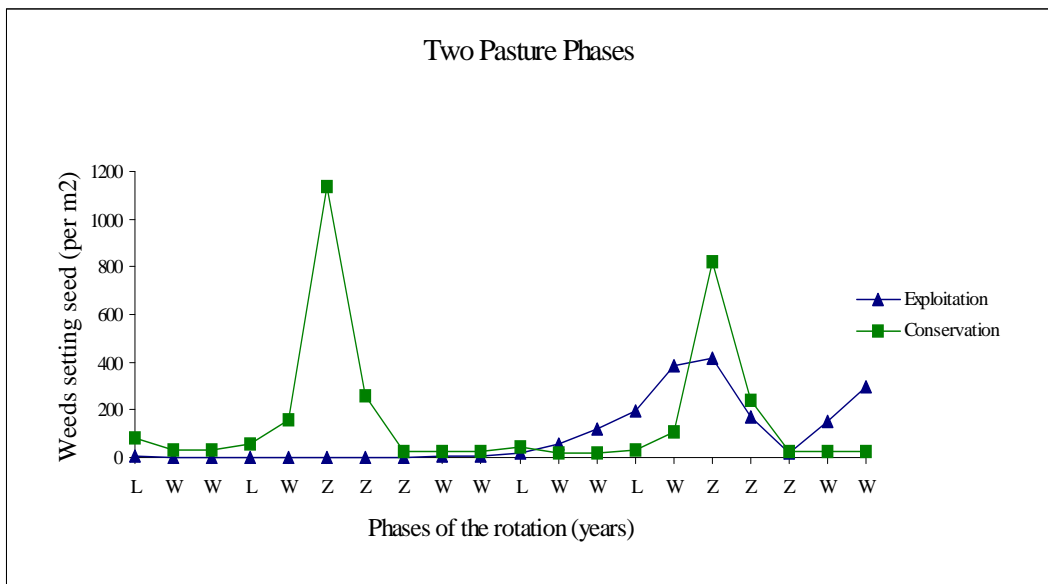


Figure 3. Weed density in each of the 20 years of a cropping sequence with two pasture phases (W- wheat, L- lupins, Z- cadiz serradella pasture)

From the results presented in Table 2 and the trends shown in Figures 1, 2 and 3, it is possible to see that for all three rotations there is a much better long-term control of weed numbers under conservation than under exploitation (although there are periods of high density during the 20 years). This difference is specially marked for continuous cropping, with finishing weed densities of 755 per m² under exploitation

in contrast with 110 weeds under conservation. The gap is reduced for the sequence with one pasture phase (516 versus 152 weeds) and even more for the one with two pasture phases (109 versus 25 weeds).

Because pasture provides better weed control than cropping due to grazing and the use of non-selective herbicides, weed density decreases as pasture increases in the rotation. This fact is supported by the lower finishing weed numbers under pasture shown in Table 2. However, when comparing Figures 2 and 3, it can be seen that weed density is a lot higher in years 16 and 17 for the sequence with two pasture phases. The reason for the high density in year 16 is that it is not worth including a 20-day delay in sowing of Cadiz in the conservation strategy, which proves profitable in the exploitation strategy. It is an expensive practice when much cheaper weed control with Hoegrass is available a couple of years later.

Net Value of Conservation

The main result is that the benefits from conservation are relatively low, in spite of the better long-term weed control provided by this strategy. However, the obtained results actually indicate an increase in the net value of conservation as pasture increases in the rotation, whereas our hypothesis was that it would decrease. This is demonstrated by the figures shown in Table 2 for the value of conservation: -\$10/ha for continuous cropping, -\$3/ha for one pasture phase and \$3/ha for two pasture phases. The explanation for this result lies on the difference in gross margin between exploitation and conservation. In both continuous cropping and two pasture phases, conservation results in lower profits early on, but higher profits later in the period. In the case of cropping, there are some years of huge losses (especially year 7) from the conservation strategy, before the benefits occur. This doesn't happen in the two-pasture-phase case, because the first pasture phase is brought in at exactly that point and so avoids a big loss. It also is avoided in the one-pasture-phase case because the pasture phase frees up one use of Hoegrass, which can be moved forward to prevent the “blow out” in year 7.

As noted earlier, our original hypothesis was that conservation is more valuable in circumstances where weed density has greater potential to increase in the future. This would mean that conservation is more favoured under continuous cropping, since this offers less scope for controlling weeds after resistance has developed. However, the results have shown that a pasture phase early on increases the attractiveness of a conservation strategy because it avoids a blow out in weed numbers resulting from the conservation strategy. In other words, although a pasture phase does reduce the benefits of conservation late in the period, it decreases the cost of conservation early in the period by a greater amount.

Finally, the low value of conservation indicated by the results is determined by the use of a discount rate. Because of discounting, the same profit achieved early in the period is worth more than one later on. Therefore, even though exploitation does allow weed densities to increase at the end, the costs of this are heavily discounted, whereas the benefits of exploitation all occur early on when discounting is low. Therefore discounting generally favours exploitation.

Reduced Weed Control

A sensitivity analysis was conducted on the intensity of weed control with the purpose of investigating its impact on the net value of herbicide conservation. Thus, a situation of reduced weed control was simulated based on delayed sowing, where the second year of a wheat phase was now treated the same way as the first year wheat. In the new scenario, sowing of wheat was delayed 10 days when Hoegrass was not used, instead of having a 20-day delay. Likewise, the second wheat was now sown at the first opportunity when applying the herbicide, rather than sown 10 days after the opening rains.

As the figures in Table 3 demonstrate, the weed numbers are higher and the net value of conservation is lower now, in comparison to a situation of good weed control. As before, the difference is smaller under the sequence with two pasture phases (\$3/ha/yr), where the initial costs of conservation are reduced by the first pasture phase. This difference gradually increases under the sequence with one pasture phase (\$7/ha/yr) and continuous cropping (\$9/ha/yr). An increase in the rate at which the weed population increases means that the cost of the conservation strategy early in the period is increased. This is consistent with the explanation for the trend with pasture phases.

Table 3. Effect of herbicide exploitation and conservation, in a low weed control strategy, on NPV per hectare and weed density under three different enterprise sequences. The net value of conservation is also represented

	Continuous Cropping		1 Pasture Phase		2 Pasture Phases	
	NPV (\$/ha)	Weeds setting seed ^A	NPV (\$/ha)	Weeds setting seed ^A	NPV (\$/ha)	Weeds setting seed ^A
Herbicide Exploitation	109	1410	118	1221	109	316
Herbicide Conservation	90	360	108	598	109	41
Net value of Conservation	-19		-10		0	

^AAverage over the last three years.

These results suggest that in strategies where big losses occur in early years, such as in the continuous cropping conservation strategy, it may be worth giving up some benefits later by using one of the herbicides' shots to avoid the weed blow out at the start. This issue requires further research.

CONCLUSION

When comparing the scenarios of herbicide exploitation and conservation, the overall conclusion is that the net benefits from conservation are low, although this strategy provides a better weed control over the 20-year period. This result is enhanced in a situation of reduced intensity of weed control where there is a greater cost early on

before the benefits of conservation start to occur. However, the inclusion of pasture in the rotation increases the attractiveness of the conservation strategy by reducing the early net losses from conservation.

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