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Discussion Paper: 3/96

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This research was funded by the Grains Research and Development Corporation

Economic Issues in Management of Herbicide-Resistant Weeds

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The authors thank Vanessa Stewart, Gurjeet Gill, Roger Cousens, John Holmes, Bill Roy, Ian Black and Christopher Preston for their various contributions to this paper. The research was funded by the Grains Research and Development Corporation.

Herbicide-resistant annual ryegrass (*Lolium rigidum*) is having a dramatic impact on the management and profitability of continuous cropping systems of southern Australia. In many cases ryegrass populations have exhibited cross resistance, where development of resistance through repeated use of one herbicide also bestows resistance to other groups of herbicides not previously used. Hence use of the major groups of selective herbicides as the predominant means of weed control is often ruled out. In this paper we discuss the development of herbicide resistance in *Lolium rigidum*, its costs and implications for farm management. Where high levels of resistance have developed, weed control strategies that included a range of control methods (such as increased crop densities, windrowing and crop topping) give the optimal return.

1. Introduction

Over the last decade substantial increases in crop yields have been made possible by the use of herbicides as the main method of weed control. While the level of herbicide use has increased, dependence on tillage and grazing for weed control have declined as many farmers have chosen reduced tillage and continuous cropping as the most profitable farming methods. However, high selection pressure from the repeated use of herbicides has resulted in several weed species rapidly evolving resistance to the major chemical groups, leading to substantial losses to farmers and a need to reassess weed control and tillage strategies.

Herbicide resistance is a bigger problem to agriculture in Australia than in any other country. Of the plant species that have developed herbicide resistance, annual ryegrass (*Lolium rigidum*) is of most significance in Australia, where the reliance on chemical weed control in continuous cropping rotations (usually involving wheat and grain legumes) has led to rapid development of this problem.

Annual ryegrass has a wide distribution and has demonstrated a remarkable capacity for rapid development of herbicide resistance. In many cases, the evolution by ryegrass of resistance to one herbicide has immediately endowed resistance to other herbicides. This development of "cross resistance" to different herbicide groups with different modes of action means that the options for control of ryegrass with herbicides are very limited, and an integrated set of weed control practices must be used. Thus herbicide resistance seems destined to radically transform the management practices of grain growers, especially in southern Australia.

The initial response of many farmers to increasing problems of herbicide resistance is to change the rate or frequency of chemical application and revert to cultivation as a means of weed control. While cultivation is the most obvious alternative, it can have long-term detrimental effects on soil structure, and may not control the problem adequately or economically.

An alternative means of control is the introduction of pasture phases into the rotation so that resistant weeds can be controlled by spray topping (spraying with glyphosate or paraquat, to which there is currently almost no herbicide resistance, prior to seed set) and grazing. The profitability of this alternative is dependent on the prices of wheat and animal products and the rate of pasture growth and hence this option is not always suitable. It also depends on the continued effectiveness of glyphosate and paraquat. While there has been only one reported case of ryegrass being resistant to glyphosate, this may change in the long term.

Farmers faced with cross-resistant ryegrass who wish to remain in a continuous cropping system must consider other methods of weed control. These may include windrowing, burning, seed catching, cycloning, preventing seed set by cutting the crop for hay, green manuring, increasing crop densities and crop topping with paraquat. (See later for explanations of these terms). Inclusion of any of these options in the system will involve a cost, and one method alone may not provide a good solution.

Our aim in this paper is to provide an overview of the main issues regarding the economically optimal management of ryegrass given the threat or actual presence of multiple resistance to a range of herbicides. We hope to raise awareness of the breadth and complexity of the issue and of the need to consider it in economic analysis of farm management practices. Examples are drawn from a range of models and from the biological literature. Most of the discussion applies only or primarily to cases of cross resistance. Management of weeds which do not exhibit cross resistance or multiple resistance is often relatively simple, at least in the short term, since it is usually possible to obtain adequate and economical control by switching to an alternative herbicide.

2. Model

In this paper, results are presented from a number of models. Apart from the results from the MIDAS model (Kingwell and Pannell, 1987), each of the models includes the following elements.

Following Pannell (1990), crop yield (Y) is represented using the following general form.

(1) $$Y = Y_0 \, [1 - D(W)]$$

where Y_0 is yield with no weeds present and D is the damage function representing the proportion of yield lost at weed density W. W includes both herbicide-resistant and herbicide-susceptible weeds (W_R and W_S respectively). W_S is a function of W_{S0}, pre-treatment density of susceptible weeds, $K(H)$, the proportion of weeds killed at herbicide rate H, and N, the proportion of weeds killed by non-chemical means.

(2) $$W_S = W_{S0}\,[1 - K(H)][1 - N]$$

The kill functions K and N must be bounded by zero and one. Resistant weeds are unaffected by herbicide, so their density depends on N but not K.

(3) $$W_R = W_{R0}\,[1 - N]$$

There are links from one season to the next via seed pools in the soil (Maxwell et al., 1990). There are separate pools for susceptible and resistant weeds. Seed production of each type depends on the total weed density. In the following season, the density of weed seedlings depends on the number of seeds and the levels of natural mortality or removal of seeds.

Profit (π) is given by

(4) $$\pi = P_Y\,Y - P_H\,H - A - F$$

where P_H is herbicide unit cost, A is herbicide application cost and F represents costs from all other inputs which are assumed to be fixed. A consists of costs of labour and machinery use which are incurred only if herbicide is applied but which are independent of the application rate, H.

3. The Issues

3.1 If farmers change rotations to delay herbicide resistance, what is the short-term cost?

The implications of introducing pasture into the cropping rotation so as to delay the development of herbicide resistance have been examined for the eastern wheat belt of Western Australia

(Bathgate et al., 1993). A linear programming model, MIDAS (Kingwell and Pannell, 1987), was used to identify the most profitable crop rotation on each of seven soil types. On soil type S2 (Sandplain) the optimum was one year cereal/one year lupins (CL), while on soil types S3 (Gravely duplex) and S4 (Duplex) it was two years cereal/one year lupins (CCL). Any alteration from these rotations to include pasture will therefore come at a cost.

MIDAS was adjusted to include nine new rotation options: PPPCLCL, PPCLC and PLC on soil types 2,3 and 4. These rotations are almost never observed currently in the region. They were selected because of the potential they offer for controlling weeds by non-chemical means, or by non-selective chemicals which seem to be at much lower risk of developing resistance. The soil types examined were those on which continuous cropping is commonly practiced.

Table 1 shows the shadow costs of these rotations: the annual losses incurred through adoption of these novel rotations rather than the optimal rotation. These losses are based on average returns per hectare over the length of the rotation, and do not directly allow for the impact of the rotation on herbicide resistance.

Table 1. The Cost of Including Pasture in the Rotation ($/ha/year) for Three Soil Types and Three Different Pasture/Cereal/Lupin Rotations (Wheat Price $170/t Wool Price 350c/kg)

	Soil type		
Rotations	S2	S3	S4
PPPCLCL	18	11	18
PPCLC	17	8	14
PLC	18	16	24

The results indicate that the introduction of a pasture phase into continuous cropping rotations can be very costly because of higher pasture establishment costs or poor pasture growth, the need for increased expenditure on broad leaf weed control in the cereal phase of the rotation and the high opportunity cost of not cropping. The profitability of these novel rotations is very dependent on soil type and product price. Given the low profit margins in the eastern wheat belt region these decreases in profit are substantial, and therefore pasture is only likely to be a viable strategy for delaying resistance on soil types which show similar profits for pasture and crops prior to the onset of resistance.

Low pasture density after cropping is a primary contributor to the relatively low profitability of pasture-cereal-lupin rotations. There are various means by which pasture production may be improved, including plant breeding, grazing management and re-seeding. However, even if pasture production in the above table could be increased by 20 percent (assuming no extra costs) substantial losses still occur (Table 2). Only on soil type S3 was a break-even situation approached. If the first two pasture rotations on S3 allow good control of resistant weeds, then the cost of herbicide resistance looks low, but on S2 and S4 the cost is still high. The results differ because of different physical characteristics of the soils, affecting yields and opportunity costs. For similar reasons, the impact of including pasture in the rotation will vary between regions.

Table 2. The Cost of Including Pasture in the Rotation ($/ha/year) for Three Soil Types and Three Different Pasture/Cereal/Lupin Rotations (assumptions as for Table 1 but pasture yield increased by 20 percent in all months)

	Soil type		
Rotations	S2	S3	S4
PPPCLCL	16	5	17
PPCLC	16	3	12
PLC	17	15	23

3.2 If farmers maintain continuous crop rotations, how long will it be before profitability collapses?

Because of the losses involved in introducing pasture into the rotation to delay herbicide resistance, farmers are likely to avoid taking this step until continuous cropping is less profitable than a system that includes pasture. Table 3 shows results from a simulation model giving the number of years of crop which can be grown before the density of weeds reaches a level at which crop is less profitable than pasture (Gorddard et al., 1996).

Table 3. The Number of Years of Crop Before Pasture Becomes a More Profitable Land Use in the Eastern Wheat Belt of Western Australia

Weeds killed by non-chemical control (%)	Weeds killed by herbicide (%)		
	0.75	0.88	0.94
0	3	7	7
25	4	9	7
50	9	9	9
75	16	16	16

The effectiveness of non-chemical control is the main determinant of years of cropping before resistant weed density reaches a critical level. Schmidt and Pannell (1996) showed that a combined chemical/non chemical control rate of over 92 percent across the rotation is necessary for continuous cropping to continue indefinitely. At the lowest herbicide dosage and zero to 25 percent effectiveness of non-chemical control, the population of susceptible weeds very quickly builds up to such high densities that cropping is less profitable than pasture. Note that the shorter durations of cropping indicated for lower herbicide dosages do not imply that cutting herbicide dosages accelerates the onset of herbicide resistance. Rather they reflect the more rapid build up of susceptible weeds when rates are cut.

3.3 What is the optimal time path of herbicide usage?

Gorddard et al. (1995) used a dynamic optimisation model to determine optimal chemical dosage and levels of non-chemical weed control. They identified an economic balance between current control of herbicide resistant weeds and future development of resistance.
They found that where herbicide resistance is present, the optimal dosage falls away rapidly in the last years of cropping as the level of resistance increases. There are several reasons for the fall in dosage:

(a) Weeds in a field crop are not all at the same stage of growth when spraying occurs, so herbicide dose can determine the level of weed survival. More mature weeds require a higher dose than smaller weeds, so the larger the dose of herbicide applied the greater the number of

weeds killed. However, once the crop is infested with resistant weeds, the yield of the crop declines and it no longer pays to apply higher herbicide doses to kill the remaining susceptible weeds, as any resulting yield increase will not cover this increased cost.
(b) Lower dose levels mean the survival of susceptible plants which can then compete with resistant plants, potentially delaying resistance development. However, biological modelling indicates that this effect is small at best (Christopher Preston, personal communication, 1995), and our economic models indicate that the direct costs from surviving susceptible weeds competing with the crop outweigh any indirect benefits from their competition with resistant weeds.

(c) Lower doses result in reduced purchase costs and reduced phytotoxic damage to the crop.

These results indicate that even with non-chemical weed control methods such as cultivation, if herbicides are used, herbicide resistance will eventually develop.

3.4 If weeds become totally resistant, can a continuous cropping rotation be maintained?

Given that cultivation and pastures provide only a partial solution to this problem, other methods of weed control must be considered. Stewart (1993) and Schmidt and Pannell (1996) have used dynamic simulation models to evaluate the economics of a variety of non-chemical weed control methods in wheat/lupin rotations in the central wheat belt of Western Australia. These non-chemical methods were used in combination with carefully selected chemicals: simazine, paraquat and/or glyphosate in lupins, and glyphosate in wheat. While it is acknowledged that trifluralin is now being used extensively in wheat crops, there is evidence that resistance has already developed to this chemical in some ryegrass populations, and so it was decided to leave it out of the analysis.

Weed control methods considered as options in the model are as follows.

- delaying sowing to allow more weeds to emerge and be killed during crop sowing;
- conducting a shallow cultivation;
- cutting the entire crop for hay to remove weed seed heads;
- green manuring (i.e., ploughing the standing crop into the soil);

- using equipment to catch weed seeds leaving the harvester with crop residues, with the seed being either burnt or removed;
- cycloning (collecting straw and seeds into bands) coupled with burning of either the bands only or whole paddock;
- crop topping lupins with paraquat (i.e., applying herbicide with a boom spray later in the growing season with the intention of preventing seed production by weeds); and
- increasing crop plant densities.

The efficacy of weed control for of each of the control methods was estimated in collaboration with weed scientists based on data on weed densities collected from field trials. A large number of strategies involving combinations of the control measures was examined. Of the control strategies investigated, a strategy which integrated six different weed control techniques provided the highest net present value (Table 4). Of course this "optimality" rest on a large number of assumptions, which are not examined in detail here. Our main point is that the better strategies tend to include a broader combination of strategies than currently in use in mainstream agriculture.

The last two strategies in Table 4 highlight the importance of employing a combination of several non-chemical control methods. In the third strategy, plant densities are not increased, while the fourth strategy relies on burning for weed control. No single control measure is close to being ranked in the five best strategies as determined by this model.

Table 4. Net Present Values (NPV) of the Two Best Weed Control Strategies and of Two Non-Optimal Strategies for Weed Control in a Continuous Cropping (Wheat: Lupin) Rotation in the Central Wheat Belt of Western Australia

This model was developed for Western Australia and would need to be adapted for use in other states. For example, the timing of both the crop-topping and windrowing operations is critical if high weed control rates are to be achieved, and the appropriate timing of these operations will vary from state to state depending on the rate at which the crop and ryegrass plants develop.

Strategy	NPV ($/ha)
Pre-spray glyphosate in wheat; use simazine in lupins; increase crop plant densities (lupins from 40 to 60 plants/m^2, wheat from 100 to 200 plants/m^2); crop-top lupins with paraquat; windrow both crops; burn windrows.	985
Pre-spray glyphosate in wheat; use simazine in lupins; increase crop plant densities (lupins from 40 to 60 plants/m^2, wheat from 100 to 200 plants/m^2); crop-top lupins with paraquat; windrow both crops; seed catch at harvest.	955
Pre-spray glyphosate in wheat; use simazine in lupins; crop-top lupins with paraquat; windrow both crops; burn windrows.	159
Pre-spray glyphosate in wheat; use simazine in lupins; increase crop plant densities (lupins from 40 to 60 plants/m^2, wheat from 100 to 200 plants/m^2); total burn after harvest.	255

4. Economic complexities of non-chemical control

Faced with resistant weeds, many farmers first consider non-chemical control methods such as burning, haying, delaying sowing, cultivating and grazing. Some of these are somewhat expensive or controversial, as outlined below. However, it is interesting to note that they were not among the methods selected by our model as providing the most profitable strategy for controlling herbicide-resistant ryegrass. This section also addresses some other complexities that may need to be considered in the economic modeling of herbicide resistance.

4.1 Short-term costs

The sowing operation itself can kill many weeds. Because the population of weeds germinates at different times, a delay in sowing results in a larger number of weeds being killed by the seeding operation. It may also allow time for an extra cultivation to stimulate germination and achieve even greater weed control. On the other hand, the yield losses due to delayed sowing can be very high (French and Schultz, 1984; Anderson and Smith, 1990). Schmidt and Belford (1993) in an experiment in the northern wheat belt of Western Australia observed an average yield loss after cultivating and delaying sowing for 12 days of 475 kg/ha for a 2,190 kg wheat crop in 1991, while Anderson and Smith (1990) showed losses of 30 kg/ha/day in the central wheat belt of Western Australia, even where the wheat variety was altered to one more suited to later sowing. Our model indicates that where it is possible to windrow crops and crop top lupins, delayed sowing should not be used.

There are also very high short term costs involved in cutting the crop for hay or green manuring. Experience indicates that many farmers are not willing to make the large short term sacrifice of crop income. As noted above, our model suggests that this may not be necessary in any case.

4.2 Increasing cultivation

Cultivation loosens and dries the soil surface and buries stubble, markedly increasing the risk of wind erosion. Results from experiments with wind tunnels show that sands have potential erosion rates one hundred times greater than those for clays, with the sandy loam texture being the cut-off point between the highly erodible sands and the more stable loams and clays (Davidson, 1989). Comparisons between cultivated and uncultivated soils showed that cultivation increased erosion rates (measured with a wind tunnel) for all soil types except highly aggregated clay. Just one cultivation reduced aggregation of dry sandy soils to a very low level (Davidson, 1989). Wind-tunnel data also showed that the greater surface roughness due to cultivation increases the drag on the soil surface and the roughened material itself is also erodible. Therefore wind erosion increases (Davidson, 1989).

Moss (1935) reported that soil drift arising from wind erosion destroys fertility by removing the fertile fraction of the soil, or by depositing material of inferior fertility on otherwise fertile fields. In areas where soil stability has declined significantly due to repeated cultivation, productivity has declined.

McFarlane and Carter (1990) simulated the effect of "sand blasting" on cereal defoliation and cereal crop yields in the south west of Western Australia. They found that one episode of sandblasting reduced yields by 9 percent, two reduced yields by 26 percent and three by 54 percent.

A further cost of cultivation is soil compaction. Henderson (1986) showed a linear increase in soil strength with an increasing number of tractor passes, resulting in the formation of a traffic pan 25 cm below the soil surface. This in turn resulted in reductions in grain yield of approximately 40 percent.

4.3 Burning

Prior to the increased use of herbicides in the seventies, burning stubble for the control of ryegrass was a recommended practice in Western Australia because of the difficulty of controlling this weed by cultivation alone. Mason et al. (1968) found that even with excellent weed control by cultivation and delays in planting to allow a number of weed germinations, late germination of ryegrass on unburnt plots gave such a dense stand of weeds that wheat growth was greatly suppressed. There was a steady decline in wheat yields where stubble was not burnt over a five year period of continuous cropping. Wheat yields declined to approximately one third of those on burnt plots at the end of this time.

In Victoria the traditional practice of burning stubble and cultivating have reduced organic matter levels and affected soil structure resulting in annual soil losses due to erosion estimated at between 2 and 30 tonne/ha (Steed, 1990). Thus burning can reduce soil structure and fertility. Raison and McGarity (1979) showed substantial losses of nitrogen when straw was burnt, while Mason (1992) found that levels of organic carbon and nitrogen in the soil were generally higher when stubble was incorporated into the soil rather than burnt.

Although the incorporation of stubble has been shown to reduce the level of inorganic nitrogen in the soil temporarily, some of the nitrogen immobilised by the stubble can be remobilised within the growing season and become available for uptake by crops. Steed (1990) took measurements over 6 years of either burning or retaining stubble and found that where stubble is retained, there are increased amounts of nitrogen in the top 20 cm of the soil after the first year.

Thus the question of burning is complex. While it is a moderately successful means of ryegrass control, it can cause substantial losses in soil fertility and cause declining soil structure, particularly on poorly structured soils such as the sand plains of Western Australia. In our model complete burning of stubble was not as efficient as limited burning of only windrows or of the seed dumps from seed catching techniques.

4.4 Problems with grazing

Annual ryegrass toxicity became a serious problem in Western Australia in the early 1970s, and rapidly spread throughout the wheat belt, resulting in the death of large numbers of sheep. The problem is most serious if sheep are allowed to graze pasture at the time when ryegrass plants are beginning to set seed, which is precisely the time when grazing is most effective as a means of weed control.

Stocking rates of 10 to 15 sheep per hectare continuously from late winter until late spring are usually necessary to substantially reduce the seed production of ryegrass (Brown et al., 1989). However stocking rates this heavy may be difficult to achieve for the whole area to be cropped in the following season. Thus, in many cases, sheep alone are not a solution to the problem of herbicide resistance and must be used in conjunction with other control methods.

4.5 Controlling other weeds with non-chemical control

One side effect of extensive use of non-chemical control methods for ryegrass may be a reduced need for chemical application for control of other species. For example, increased crop plant densities may reduce the competitiveness of broad-leaved weeds and remove the need for in-crop sprays such as MCPA or Brodal®. On the other hand, in-crop sprays may still be necessary to control later germinating weeds, so as to prevent seed contamination of the grain at harvest. Tolerance levels for some types of seed contamination in wheat are very low, (e.g., one seed per half litre for lupins, chick peas and faba beans, 5 seeds per half litre for double gees, vetch and saffron thistle) with any contamination above the threshold dropping wheat to an animal feed category with much lower sale prices.

4.6 Will carting hay spread the problem?

Hay made from herbicide-resistant ryegrass which has been cut after seed has set will contain resistant ryegrass seed. If this hay is then carted to another farm, the problem will be spread. Farmers purchasing hay also run the risk of acquiring annual ryegrass toxicity (Brown et al., 1989). The spread of either problem is dependent on the time at which the hay was cut. If the crop has not flowered prior to bailing, the risks of spreading herbicide resistance are low. We believe that some form of government intervention to discourage sale of herbicide resistance contaminated hay should be considered.

5. Conclusion

Continuous cropping systems are under threat because of the increasing problem of herbicide resistance. Serious economic losses are faced by farmers and alternative weed control methods must be considered.

The inclusion of a pasture phase in the rotation to delay the development of herbicide resistance allows for a broader range of non-chemical control methods. However the economic losses associated with including pasture can be high, depending on soil type, commodity prices and other factors.

Farmers who wish to remain in a continuous cropping system must therefore adopt strategies for weed control that include a wide range of weed control methods; no one method provides the optimal solution. Regardless of the methods adopted there will be a cost, but with careful selection of techniques the cost can be small. The corresponding reduction in reliance on chemicals may also help to enhance our "clean" farming image.

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