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Abstract

Herbicide resistant weeds are having a major impact on Australian agriculture. The most important of these is ryegrass (*Lolium rigidum*). In response to this new problem, "genetic engineering" techniques are being used to create new types of "transgenic" lupins which are resistant to non-selective herbicides to which the ryegrass is not resistant. In this study the economic value of such a herbicide-resistant lupin variety is investigated using a multiperiod bioeconomic model. The model represents a common cropping system of Western Australia in which winter crops of wheat and lupins are grown in alternate years. The ryegrass population is modelled as being completely resistant to traditionally-used selective herbicides. The net profits for a wide range of weed control measures (both chemical and non-chemical) used separately and in combination with a transgenic lupin were compared with the current options available to farmers. The best integrated strategy involving a transgenic, glufosinate-resistant lupin was found to have a similar profitability to a system based on current lupin varieties employing paraquat for in-crop spraying. However, if a glyphosate-resistant lupin were to be developed and used in conjunction with technology for physical collection or destruction of weed seeds, it was estimated that farm profits would increase by 33 percent.

Key words: transgenic crop; genetic engineering; herbicide resistance; economics; weeds; lupin; wheat; ryegrass; *Lolium rigidum.*

Introduction

Herbicide-resistant annual ryegrass (*Lolium rigidum*) is having a dramatic impact on the management and profitability of continuous cropping systems of southern Australia (Bathgate, Schmidt and Pannell, 1993). In many cases ryegrass populations exhibit cross resistance (Powles and Holtum, 1990), where development of resistance through repeated use of one herbicide type also bestows resistance to other groups of herbicides not previously used. Hence, use of the alternative major groups of selective herbicides as the predominant means of weed control is often ineffective.

Recently, the Co-operative Research Centre for Legumes in Mediterranean Agriculture (CLIMA) at the University of Western Australia has developed a transgenic Lupin that is resistant to the herbicide glufosinate. While this chemical is currently used for targeted weed control in horticultural crops, it has not been used in field crops. The perceived advantage of a glufosinate-resistant lupin is the potential to control both ryegrass and broad leaved weeds after emergence of the crop.

The concept of developing herbicide-resistant in crops plants is not new. The first herbicide-resistant crop to be bred and introduced was a triazine-resistant spring canola (oil seed rape) developed by transferring a cytoplasmic-inherited triazine-resistant trait from *Brassica campestris* to *B. napus* via conventional plant breeding techniques (Beversdorf, Hume and Donnelly-Vanderloo, 1988). Subsequently, herbicide resistance was bred into a number of crops including corn (Newhouse, Singh, Shaner and Stidham, 1991), tobacco and tomatoes (Lee, Townsend, Tepperman, Black, Chui, Mazur, Dunsmuir and Bedrook, 1988).

Procedures used for conferring resistance include (a) selecting for resistance in natural or mutagenised populations, (b) using cell/tissue culture techniques to identify genetic material carrying natural resistance and incorporating this material into commercial cultivars by conventional breeding, (c) using genetic engineering to incorporate genes conferring herbicide resistance into establish commercial cultivars of crop plants (Huppatz, Llewellyn, Last, Higgins and Peacock, 1995). In the case of lupins, resistance has been conferred by genetic engineering using material derived from *Streptomyces* species (Donn, Dirks, Eckes and Uijtewaal, 1990).

This paper is an examination of the likely economic impact of the herbicide-resistant lupin in circumstances where ryegrass exhibits total resistance to three major groups of chemical herbicides commonly used for control of grass weeds: aryloxyphenoxypropionates (e.g. diclofop-methyl), cyclohexanediones (e.g. tralkoxydim) and sulfonyl ureas (e.g. chlorsulfuron). Most farms in Western Australia do not currently have total resistance to all three herbicide groups. However available evidence indicates that their continued use will soon result in this situation (Gill, Martin and Holmes, 1993).

While it is true that trifluralin is now taking the place of these chemicals in wheat/lupin rotations in Western Australia, there is evidence that resistance to trifluralin is developing and will not provide a long term solution. For this reason trifluralin is not considered as an alternative weed control method in this analysis.

Our approach in this paper is to determine whether herbicide-resistant lupins will play a role in the most profitable integrated weed management strategy and to estimate the improvement in profit resulting from their use. This approach is applied twice: first for a lupin variety resistant to glufosinate and then for a lupin variety resistant to glyphosate. The second case is hypothetical at this stage. This analysis is intended to contribute to decisions about potential future research to develop such a lupin.

In all scenarios, the farming system modelled involves winter crops of wheat and lupins grown in alternate years. Each crop is sown in late autumn or early winter (April to June) and harvested in November (lupins) or December (wheat). This rotation is widely practised on light textured, low pH soils which are common in Western Australia. Most farms in the modelled region are between 1500 and 5000 hectares in area, include a mixture of soil types, and have a mixture of cropping and livestock enterprises. The wheat-lupin rotation was chosen for analysis because it is the farming system involving the greatest incidence of herbicide-resistant weeds.

The model

Weed growth and control

Seeds present at the beginning of a given year (S) may or may not germinate. G represents the proportion which does germinate. Those which germinate may die naturally (M_a) or be killed by non-chemical control (M_n). If a herbicide is applied, a proportion (M_c) of weeds is killed. Seeds which remain ungerminated either die naturally or add to the following year's seed bank. It is assumed that resistant weeds are totally unaffected by the three herbicide groups mentioned earlier. The density of weeds which survive to maturity (W) is given by

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

Mortalities are measured as proportions of weeds killed. Weed controls are conducted sequentially and therefore are multiplicative (rather than additive) in their impacts on weed numbers. Levels of mortality from the various control measures were estimated by weed scientists in Western Australia based, in the main, on results of field experiments. Assumed mortality levels are shown in Table 1.

Table 1. Assumed proportion of ryegrass mortality for weed control strategies used in the model, based on limited experimental data.

Control method	Crop	Proportion of ryegrass weed mortality
Green manuring the crop	Wheat or lupins	0.86
Haying the crop	Wheat or lupins	0.67
Burning crop residues	Wheat or lupins	0.61
Catching weed seeds behind harvester, dumps burnt	Lupins	0.60
Catching weed seeds behind harvester, dumps removed	Lupins	0.58
Cycloning the crop, cyclone trail burnt	Lupins	0.61
Cycloning the crop, whole paddock burnt	Lupins	0.64
Windrowing the crop, windrow burnt	Lupins	0.80
Windrowing the crop, seeds caught behind harvester	Lupins	0.80
Cultivation, one month delay in sowing time	Wheat or lupins	0.50

Cultivation, 10 days delay in sowing time	Wheat or lupins	0.40
Catching weed seeds behind harvester, dumps burnt	Wheat	0.60
Catching weed seeds behind harvester, total burn	Wheat	0.68
Cycloning the crop, cyclone trail burnt	Wheat	0.61
Cycloning the crop, whole paddock burnt	Wheat	0.64
Windrowing the crop, windrow burnt	Wheat	0.80
Windrowing the crop, seeds caught behind harvester	Wheat	0.80
Herbicides		
Simazine	Lupins	0.60
Glufosinate, 2 sprays	Transgenic lupins	0.50
Glyphosate	Transgenic lupins	0.90
Glyphosate or paraquat/diquat at sowing	Wheat or lupins	0.25
Crop top (paraquat or glufosinate)	Lupins	0.90
Diclofop-methyl (if no resistance)	Wheat	0.94
Fluazifop-p (if no resistance)	Lupins	0.94
MCPA /Diflufenican	Wheat/Lupins	0
Chlorsulfuron (if no resistance)	Wheat	0.94

Further explanation of some of the control methods is necessary. Green manuring means ploughing the standing crop into the soil. This is done prior to the weeds setting seeds and so although it involves a substantial sacrifice of revenue, it is a very effecting method of weed control. Haying the crop means cutting and baling the crop as hay and removing bales from the paddock. This is conducted prior to weeds shedding seeds. Catching weed seeds involves towing a cart behind the harvester to collect seeds and chaff, which are left in dumps for later removal or burning. A "cyclone" is a fitting attached to a harvester which allows placement of fine harvest residues (such as ryegrass seeds) on top of the harvester trail. This placement enhances seed mortality during burning of the residues, and has benefits in allowing a smaller proportion of the paddock to be burnt (reducing the risk of wind erosion of bare soil). Windrowing means cutting the crop and laying it in rows prior to harvest. This also concentrates the weed seeds in bands which can be burnt after harvest, or removed using seed catching technology. Cultivation means ploughing prior to sowing the crop. The term "in-crop spraying" (used later) means applying herbicide with a boom spray within two months of crop emergence. The term "crop topping" (also used later) means applying herbicide with a boom spray later in the growing season with the intention of preventing seed production by weeds.

Phytotoxic damage

For the simazine and diclofop-methyl treatments, a simple proportional reduction in potential crop yield is assumed to result from phytotoxic damage by these herbicides.

$$Y = Y_o \ (1 - g) \tag{2}$$

where Y_o is yield with no herbicide applied and g is the proportion of Y_o lost due to application of herbicide treatment. For simazine used in lupins, $g = 0.0375$, while for diclofop-methyl used in wheat $g = 0.054$ (Pannell, 1990b).

Where paraquat is used for crop topping (in-crop spraying of almost-mature weeds to prevent seed formation) causes yield losses of either 10 or 15 percent (based on farmer and consultant experience), resulting from phytotoxicity and physical passage of the spray boom. It is assumed that pre-season sprays such as glyphosate and paraquat/diquat have no effect on grain yield.

Weed seed production and crop grain yield

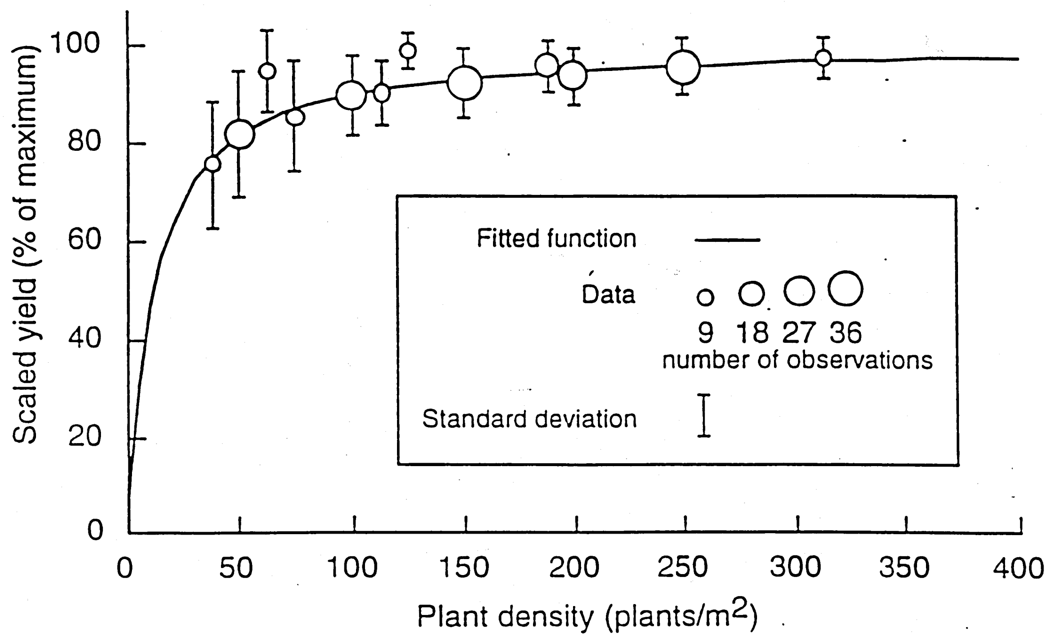
The seed yield of each crop is reduced by competition with ryegrass according to the following equation adapted from Maxwell, Roush and Radosevich (1990).

$$Y_1 = \frac{P_1.m_1}{a + P_1 + P_2.k_{1,2}} \tag{3}$$

Subscript 1 denotes the crop, subscript 2 denotes the weed, P is plant density (plants/m^2), a is a constant, and $k_{1,2}$ is the competitive effect of species 2 on species 1. The value of m_1 is derived by Diggle (unpublished), based on Figure 1 which is reproduced from Anderson and Barclay (1991). It is calculated as:

$$(4) \qquad m_1 = \frac{M_1 . P_t + b}{P_t}$$

where M_1 is the maximum observed crop yield in the absence of competition at a set plant density P_t, and b is a constant for the crop being considered. Early results from plant density/yield trials for lupins indicate that the value of the constant b is different than for wheat. The same equation (with different parameter values and subscripts 1 and 2 changed) is used to represent the effect of competition by each crop on seed production by ryegrass.



Values for the parameters of equation (3) for the various types of competition examined are given in Table 2. These parameter values were selected by callibrating the equation to reproduce results of field experiments.

Table 2. Values of competition parameters for ryegrass, wheat and lupins (see equation 3)

Species 1	Species 2	Units of m_1 and Y	m_1	a	P_1	$k_{1,2}$
wheat	ryegrass	tonnes/ha	2	11	100	0.3
lupins	ryegrass	tonnes/ha	1.2	7	40	0.1
ryegrass	wheat	seeds/m^2	31000	25	-	3
ryegrass	lupins	seeds/m^2	31000	25	-	7

Estimation of parameters for the seed production and mortality models was extremely difficult. While there have been numerous studies of competition between ryegrass and wheat, none have been designed and measured to allow estimation of all of the parameters of this seed production model. The great variability of ryegrass biology across soil types, seasons and regions is reflected in the variability of the parameters that have been measured. For example, reported estimates of natural seed decay over summer range from 0 to 50 percent depending, largely, on the amount of summer rain. Estimates of the proportion of seeds that remain dormant all season and germinate the following year vary from 1 to 20 percent (Howat, 1987). The variation appears to be due to differences in climate and cultivation practices (Gramshaw, 1972). There is even less information about the competition effects of ryegrass on lupin production. Our response to this problem was to rely on subjective estimates of weed scientists at the Department of Agriculture, Western Australian. The estimates are intended to reflect conditions in a typical year in the study region.

Costs of cropping

Costs are divided into fixed and variable costs. In this study only costs associated with the decision variables (types of herbicides, types of non-chemical control measure, method of harvesting and seeding rates) are considered variable. Other cropping costs such as those of fertiliser and transport are considered fixed, and are based on data in a current version of the MIDAS whole-farm linear programming model (Kingwell and Pannell, 1987; Pannell and Bathgate, 1991). It is assumed that all labour is carried out by the farmer, and therefore labour costs are not included in the model. The only exception is where the crop is cut for hay, in which case contract labour costs are included. It is assumed that seed for the herbicide-resistant lupin only needs to be purchased once ever, which means that any cost difference compared to current seed will be trivial over the 20 year period considered in this study. We ignore this difference.

Costs of the various weed control options were estimated in detail. The estimated costs include costs of purchasing, maintaining and operating machinery and equipment, costs of purchase and application of herbicides and costs of crop yield forgone due to practices such as cutting it for hay, green manuring and delayed sowing. Table 3 shows the estimated costs of each of the control options included in the model. Up-front purchase costs are converted to annual equivalents for the purpose of calculating these costs.

Table 3. Estimated costs of weed control options.

Weed control method	**$/ha**
Green manuring the crop - direct cost	30.00
Green manuring the crop - income loss	127.60*
Haying the crop - direct cost ($/tonne)	20.00
Haying the crop - income loss	15.33*
Burning crop residues	0.00
Catching seeds behind the harvester (annual repayment)	1.25
Catching seeds behind the harvester (operating cost)	1.49
Cycloning (annual repayment)	0.52
Cycloning (operating cost)	1.13
Windrowing (annual repayment)	2.27

Windrowing (operating cost)	6.27
Cultivation	3.02
Delay sowing by 10 days	12.68*
Glufosinate (chemical plus application)	23.00
Simazine (chemical plus application)	12.80
Glyphosate (chemical plus application)	13.60
Crop top paraquat (chemical plus application)	6.41
Crop top glufosinate (chemical plus application)	35.40

*Income loss when using these methods depends on the weed burden in the crop in each particular year. Figures presented are for the first lupin crop in scenario 2b.

Profit and net present value

Annual net profit (R) from cropping one hectare is given by

(5) $$R = P_w \; Y - C_n \; - C_h \; - C_f$$

where P_w is crop sale price, Y is yield, C_n is the cost of non-chemical control, C_h is the cost of herbicides, and C_f is fixed costs. The farm-gate prices of wheat and lupins were assumed to be \$120/tonne and \$150/tonne respectively. The model is run for a 20 year time frame (T), so costs and returns must be discounted to make them comparable at a particular point in time: in this case, the start of the period. A real discount rate (r) of eight percent per year is used. The objective represented in the model is to maximise the so-called "net present value" (NPV), which is the sum of discounted net profits. The decision variables are the levels of various weed control options in each year, which combine to produce particular levels of chemical weed control (M_{ct}) and non-chemical weed control (M_{nt}) in each year, t.

In summary, the farmer's weed control problem can then be written as

(6) $$\text{MAX} \quad NPV = \sum^{T} (P_w \; Y_t \; - C_{nt} \; - C_{ht} \; - C_f)/(1+r)^t$$

$M_{ct} M_{nt}$ $\quad t=1$

Tables 4 and 5 show the assumed parameter values, yields and costs used in the analysis.

Table 4. Parameter values and yields assumed in the model.

Parameter	**Value**
Lupin density (plants/m^2)	40
Wheat density (plants/m^2)	100
Wheat sowing rate (kg/ha)	60
Lupin sowing rate (kg/ha)	80
Maximum wheat yield (kg/ha)	2000
Maximum lupin yield (kg/ha)	1800
Yield loss from delaying sowing by one month (proportion)	0.23
Yield loss from delaying sowing 10 days (proportion)	0.08
Wheat hay price net of mowing and transport costs ($/kg)	0.09
Lupin hay price net of mowing and transport costs ($/kg)	0.07
Maximum ryegrass seed production (seeds/m^2)	31,000
Initial weed density (plants/m^2)	1
Seedling mortality factor (percent)[1]	20
Dormant seeds (percent)[2]	20
Viable weed seeds carried over to following year (percent)[3]	0.6
Viable weed seeds carried over to two years later (percent)[4]	0.1
Harvest index of wheat (proportion)	0.32
Harvest index of lupins (proportion)	0.3

[1]seeds which die after germinating

[2]percent of seeds which are dormant, and so fail to germinate at time of seeding

[3]the percent of those seeds which failed to germinate in the first year, which are still viable in the following year.

[4]the percent of those seeds which failed to germinate in the first year, which are still viable two years later.

Table 5. Production costs and rates assumed in the model.

Item	**Cost or rate**
Superphosphate fertilizer ($/t)	175
Rate of superphosphate fertilizer for wheat (kg/ha)	80
Rate of superphosphate fertilizer for lupins (kg/ha)	100
Price of urea fertilizer ($/t)	316
Rate of urea fertilizer for wheat (kg/ha)	76
Fuel cost $/L	0.4336
Seed dressing cost for wheat ($/ha)	1.08
Seed grading and cleaning cost for wheat ($/ha)	0.72
Seed purchase and inoculation cost for lupins ($/ha)	17.6
Seed grading and cleaning cost for lupins ($/ha)	1
Insurance rate for wheat (%)	0.86
Insurance rate for lupins (%)	1.04
Rail freight ($/t)	17
Farm to bin transport cost ($/t)	5
Machinery repairs and maintenance cost: direct drill ($/ha)	1.4
Machinery repairs and maintenance cost: shallow cultivation ($/ha)	1.3
Machinery repairs and maintenance cost: harvest ($/ha)	4.5
Oil, fuel and grease cost: direct drill ($/ha)	2.311
Oil, fuel and grease cost: shallow cultivation ($/ha)	4.032
Oil, fuel and grease cost: harvest ($/ha)	3.345

Simplifications and limitations

While our model represents many aspects of the biology of weed competition, population dynamics and mortality, there are a number of areas in which simplifying assumptions have been made. The model is deterministic. We do not represent the year-to-year variation in weed growth or herbicide performance, the spatial variation in herbicide dose (Dorr and Pannell, 1992) or the impact of risk aversion of the optimal management strategy (Pannell, 1991). However, other published evidence indicates that the impacts of risk on optimal management strategies for ryegrass are small (e.g. Pannell, 1990a; Dorr and Pannell 1992).

The model is not an optimisation model. "Optimal" strategies for different scenarios are identified by extensive simulation of many strategies. Choice of strategies is guided by a number of heuristic tools, but given the complexity of some of the integrated strategies, it is possible that in some cases we fail to identify the truly optimal strategy.

We assume that weeds other than ryegrass are well controlled through the use of chemicals (MCPA, paraquat/diquat, glyphosate and diflufenican). Reports of herbicide resistance in Australia have been predominantly due to ryegrass, with wild oats (*Avena* spp.) accounting for the only other commercially significant reports (Powles and Holtum, 1990).

A final simplification is the exclusion of a potential management strategy from the analysis: rotation of crop with pasture (with prospects of reduced weed seed numbers through grazing and other means). All results presented here are for a continuous cropping rotation of one year wheat/one year lupins. This is the rotation within which herbicide resistance has been most commonly observed in Western Australia.

In attempting to estimate some parameters of the model, we identified deficiencies in the quality and/or quantity of available data. This is especially true for the seed bank dynamics component of the model (equations 1, 2 and 6), the lupin density response, the mortality values assumed for different control measures, and the effect of glufosinate on seed yield of the reistant lupins under different crop densities.

Results and discussion

Scenario 1: Chemical control only

Conventional farming system - no herbicide resistance (1a)

In the conventional farming system, where herbicide-resistant weeds were not a problem, farmers relied on a combination of chemicals to control ryegrass. In the model for this scenario, grass control is by glyphosate and chlorsulfuron in wheat, and by gylpohsate, simazine and fluazifop-p in lupins, while MCPA and diflufenican are used for control of broad leaved weeds in wheat and lupins respectively. Assuming (unrealistically) that herbicide resistance does not develop, the NPV over 20 years using this strategy is $1010/ha (Table 6).

Table 6. NPV over 20 years and equivalent annual value of net returns (annuity), and final weed density for each weed control scenario.

	Scenario[1]	NPV	Annuity	Final weed density[2]
1a	Conventional practice, no herbicide-resistant weeds	1010	103	<1
1b	Conventional practice, herbicide-resistant weeds	-573	-58	9213
1c	1b with glufosinate in-crop & crop topping	-462	-47	3643
2a	Increase crop densities, delay sowing	250	25	538
2b	Increase crop densities, paraquat crop topping	985	100	19.7
2c	2b no paraquat, glufosinate in-crop & crop topping	1001	102	6.04
	2c 50% drop in price of glufosinate	1128	115	6.04
	2c glufosinate efficacy 70%	1023	104	0.68
	2c 50% price drop, 70% glufosinate efficacy	1150	117	0.68
2d	2b no paraquat, glufosinate crop topping only	926	94	19.7
	2b 50% drop in price of glufosinate	1003	102	19.7
3a	2b no paraquat, 2 in-crop glyphosate sprays	1301	133	0.36

3b	3b 3 in-crop glyphosate sprays	1235	126	0.01
3c	2b no paraquat, 1 in-crop glyphosate spray	1150	117	19.7
3d	3b windrowing lupins replaced by crop topping	1206	123	0.06

[1] With or without pre-crop glyphosate sprays, simazine and windrowing (refer text). Throughout the model glyphosate is used at the rate of 1 L/ha. Where weed numbers are very small, lower rates may be optimal. If so, these would result in very slightly higher NPVs and annuities than are presented.
[2] Average plants/m^2 of final 2 years

With herbicide resistance (1b)

Once herbicide resistance is introduced into the weed population, chlorsulfuron and fluazifop-p are no longer options and the farmer's NPV falls to -\$573/ha. Obviously, given this negative return, cropping would cease.

With glufosinate-resistant lupin (1c)

If we introduce a glufosinate-resistant lupin into the rotation, and use 2 in-crop sprays of glufosinate and one "crop top" using glufosinate, the NPV improves only slightly to -\$462/ha. Thus even with the availability of a herbicide-resistant lupin, it is no longer possible to rely on chemicals alone for weed control. In the following section we investigate the inclusion of a wide range of non-chemical control measures.

Scenario 2: Chemical and non-chemical control

Increase crop densities, delay sowing (2a)

In this scenario, the farmer decides to use a combination of methods to combat ryegrass without using a herbicide-resistant lupin. The simplest and most cost-effective method is to increase the density of wheat plants/m^2 from 100 to 200 which increases the competitiveness of wheat relative to ryegrass. As well as this, the best strategy (i.e. the one which maximises NPV) includes increasing the lupin plant density from 40 to 60 plants/m^2, delaying sowing of both wheat and lupins by 10 days, and windrowing both crops prior to harvest. The delay in seeding allows time for more weed seeds to germinate by the time seeding occurs. It also gives the farmer time to include an extra cultivation before seeding, which again kills more of the weeds. Windrowing concentrates weed seeds into bands which are then burnt. With these methods the NPV is $250/ha (Table 6).

Increase crop densities, paraquat crop-topping (2b)

Although not yet registered for this use, very many farmers in Western Australia are considering using paraquat for "crop topping" in lupins, (the National Registration Authority has indicated that registration of paraquat is expected late in 1995). The herbicide is sprayed as weeds are flowering and seed production is dramatically reduced. Crop topping can lead to lupin yield losses of between 10 and 15 percent due to phytotoxicity and passage of the boom spray. Even so, when scenario 2a is combined with crop topping, assuming a 10 percent yield loss, the reduction in weed seed production increases the farmer's NPV to $985/ha, which is within $25/ha of the original return before development of herbicide resistance (scenario 1a).

When crop topping is used, delayed sowing of both wheat and lupins is no longer necessary, nor is it optimal to use a pre-crop spray of glyphosate in lupins. If paraquat causes 15 percent loss, the NPV drops to $940/ha.

Use glufosinate in crop and for crop topping (2c)

In this scenario, paraquat is replaced by glufosinate (using 2 in-crop sprays and one crop top) and the glufosinate-resistant lupin is grown. In this case, it is optimal to use the same strategies of windrowing and increased plant densities as in scenario 2b. It is no longer necessary to use diflufenican, nor economic to use a pre-crop application of glyphosate in wheat and lupins. The resulting NPV is $1001/ha, slightly higher than that achieved where paraquat is used with a 10 percent yield loss (Table 6). This is based on the assumption that there is no phytotoxic yield loss in the lupins due to glufosinate. If yield loss when using the glufosinate-resistant lupin were actually 10 percent (as for paraquat), the NPV would fall to $909/ha, somewhat less than when using paraquat in scenario 2b. Thus, given our standard assumptions, the question of whether the glufosinate-resistant lupin can increase profits depends partly on whether it suffers any phytotoxic yield loss.

In the above examples, paraquat is used only once (for crop topping) while glufosinate is used three times, twice as an in-crop spray and once for spray topping. A contributor to the lower returns in scenario 2b (using paraquat) is the high cost of using diflufenican for in-crop control of broad-leaved weeds, without obtaining any control of ryegrass (Table 7). In contrast, glufosinate controls both ryegrass and broad leaved weeds.

Table 7. Cost of chemical control options.

Chemical	$/ha
Glufosinate, two in-crop sprays	20.00
Glufosinate, one crop top	30.00
Glyphosate, one in-crop spray	10.60
Paraquat, one crop top	3.41
Diflufenican, one in-crop spray	12.44

Use glufosinate for crop topping only (2d)

If glufosinate is used only for crop topping and not as an in-crop spray, it becomes optimal again to use diflufenican in lupins and glyphosate prior to planting of wheat. However this strategy is inferior to 2c, reducing the NPV to $926/ha (Table 6). This option would only be realistic if farmers expected phytotoxic damage of more than 15 percent when using paraquat (scenario 2b), and of around four percent from in-crop use of glufosinate.

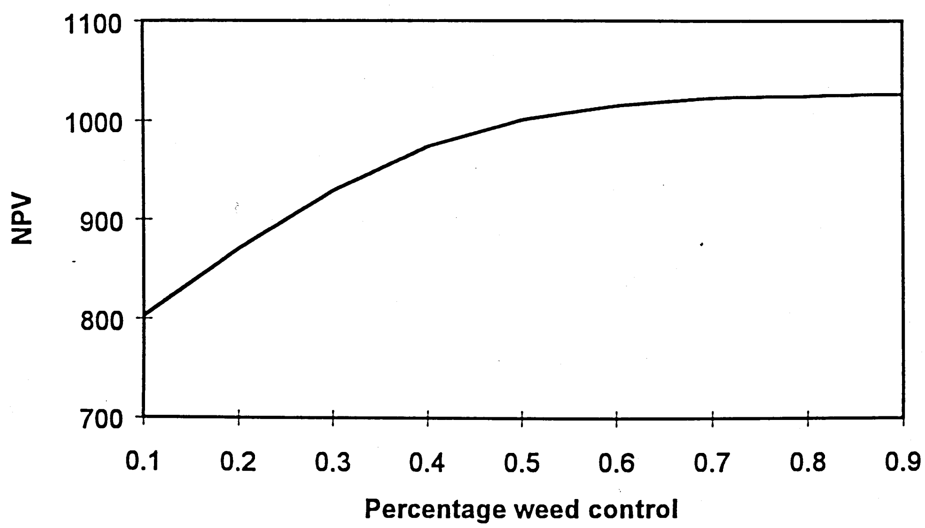
If the farmer has good broad-leaved weed control from using MCPA in wheat and thus does not require either diflufenican or an in-crop spray of glufosinate in lupins, the NPV for scenario 2c rises to $1005/ha. However this is less than the $1063/ha which would be achieved if diflufenican could be removed from scenario 2b.

Changing the efficacy and/or price of glufosinate

Currently glufosinate is only registered in Australia for use on horticultural crops. One might expect that if it became widely used on broadacre crops, its price would fall. If the price of glufosinate was to fall by 50 percent to $10/L (i.e. comparable to the price of glyphosate), then the NPV for scenario 2c would increase by 12.7 percent to $1128/ha, which is 14.5 percent greater then for the paraquat-based strategy 2b. A glufosinate price fall of 50 percent in 2d would provide an increase in income of 8.3 percent to $1003/ha, so that glufosinate is slightly more profitable than paraquat (strategy 2b) even without in-crop use. The main reason why the NPV is higher in scenario 2c is that when glufosinate is used both in-crop and for crop topping, there is no need to use diflufenican for control of broad leaved weeds.

To this point we have assumed that the two in-crop sprays of glufosinate give combined control of only 50 percent of ryegrass weeds. If this percentage is raised to 70 percent, the NPV of strategy 2c increases from $1001 to $1023/ha. A price drop of 50 percent combined with an increase in efficacy to 70 percent results in an NPV of $1150/ha for scenario 2c. These results indicate that a given percentage change in the price of glufosinate has a greater effect on the NPV than does the same percentage change in its efficacy. Increasing glufosinate efficacy has a relatively small effect on NPV because of the ryegrass control already being achieved through use of simazine (60 percent mortality), windrowing (80 percent) and crop topping of lupins (90 percent). Figure 2 shows the diminishing marginal increase in NPV achieved by increasing the percentage weed control of glufosinate.

Crop Protection, C. Schmidt and D. Pannell, Figure 2.

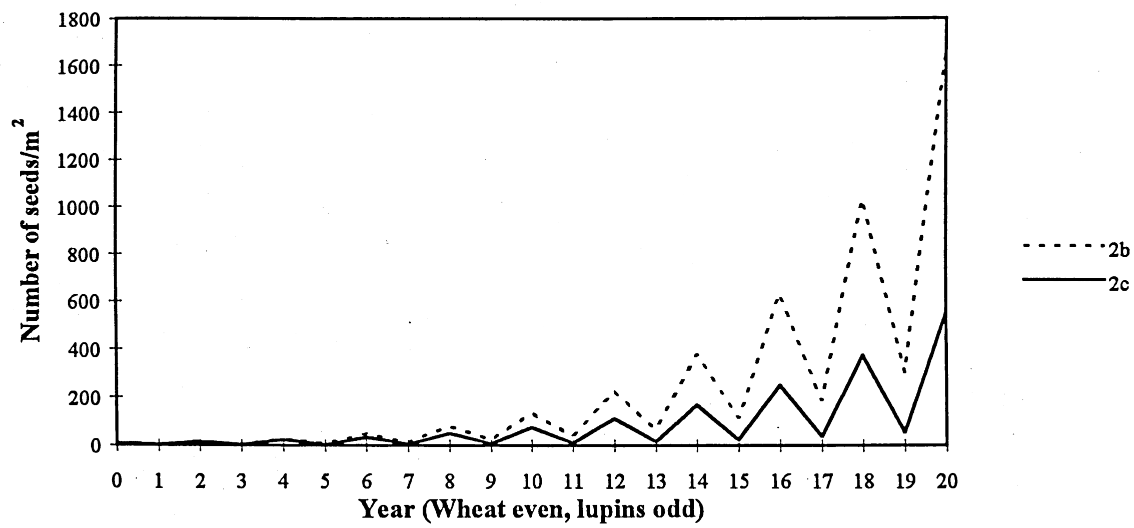


Given that the expected weed mortality from glufosinate is low (0.5), in practice we would expect it to vary substantially from year to year (e.g. Pannell, 1990b). From the analysis of Pannell (1990a) we would expect that this variability would result in higher average weed densities compared to the predictions of our deterministic model. Representing the variability in the model would reduce the NPV of strategies which include glufosinate.

Seed numbers

The two best strategies so far are 2b (which excludes a herbicide-resistant lupin) and 2c (which includes a herbicide-resistant lupin). Figure 3 shows ryegrass seed numbers produced each year over the 20 year period for these two strategies. Weed control in the lupin phase is poorer in scenario 2b than in 2c, and this is a major cause of the lower NPV for 2b ($985 versus $1001). It is apparent from Figure 3 that neither of these strategies maintains the weed population at low levels indefinitely.

Crop Protection, C. Schmidt and D. Pannell, Figure 3.



Scenario 3: Glyphosate-resistant lupin

The following strategies employ chemical and non-chemical control measures in combination with a different, as-yet hypothetical, transgenic lupin resistant to glyphosate. The aim of this analysis is to contribute to the decision of whether development of such a lupin should be pursued.

Use glyphosate in lupin crop twice (3a)

In this scenario, we consider the economics of the development of a transgenic lupin resistant to a low cost herbicide (such as glyphosate) which has better non-selective weed control. If we continue to assume that the herbicide has no effect on grain yield of the herbicide-resistant lupin and that its yield is as high as that of the current lupin varieties, then the best results come from a strategy similar to the optimum for scenario 2a. It involves the same high plant densities and windrowing of both wheat and lupin crops as used in scenario 2a, but two in-crop applications of glyphosate to lupins replace crop topping of paraquat, application of diflufenican for control of broad-leaved weeds (as glyphosate will control them), and pre-crop applications of glyphosate. The NPV for this strategy is $1301 (Table 6), which is substantially higher than the results for glufosinate and higher than the conventional practice, even without herbicide resistance (scenario 1a).

Clearly the benefits of this glyphosate-resistant lupin are substantial, even in circumstances where there is no herbicide resistance in the weed population. The reasons for the increase in NPV are:

(a) The replaced practice of crop topping with paraquat involved yield losses due to phytotoxicity;

(b) Since we no longer use diflufenican for control of broad-leaved weeds (as glyphosate will control them) there is a cost saving;

(c) Since we no longer use glyphosate as a pre-crop spray in lupins there is a further cost saving; and

(d) The new optimal strategy involves using glyphosate as an in-crop spray early in the growing season, whereas the replaced paraquat option was applied late in the growing season. Consequently, the new optimal strategy involves a reduced duration of weed competition with the crop, which is reflected in different crop yield losses for the two options.

If the level of phytotoxic yield losses from in-crop application of glyphosate to lupins was to be 10 percent per spray (rather than zero), the NPV of strategy 3a would fall to $1204, which is still substantially more profitable than existing technologies.

Use glyphosate in lupin crop three times (3b)

Increasing the number of glyphosate sprays from two to three drops the maximum NPV to $1235, while any further increases in spray numbers drop the NPV even lower. This is because each additional spray kills a smaller absolute number of weeds, and for more than two sprays, the losses avoided are worth less than the cost of the spray.

Use glyphosate in lupin crop once (3c)

Conversely, reducing the number of glyphosate sprays to one drops the NPV to $1150/ha. The cost of competition from the extra surviving weeds exceeds the cost of a second spray.

Use glyphosate in lupin crop twice and crop top with paraquat (3d)

Here we investigate various strategies in which windrowing is replaced by crop topping using paraquat. In the first, windrowing of lupins in strategy 3a is replaced. Assuming that crop topping causes lupin yield losses of 10 percent, the NPV drops to $1206 (from $1301 in 3a). If additionally, windrowing of wheat is omitted the NPV falls to $820 and it is optimal to use a pre-crop spray of glyphosate in wheat.

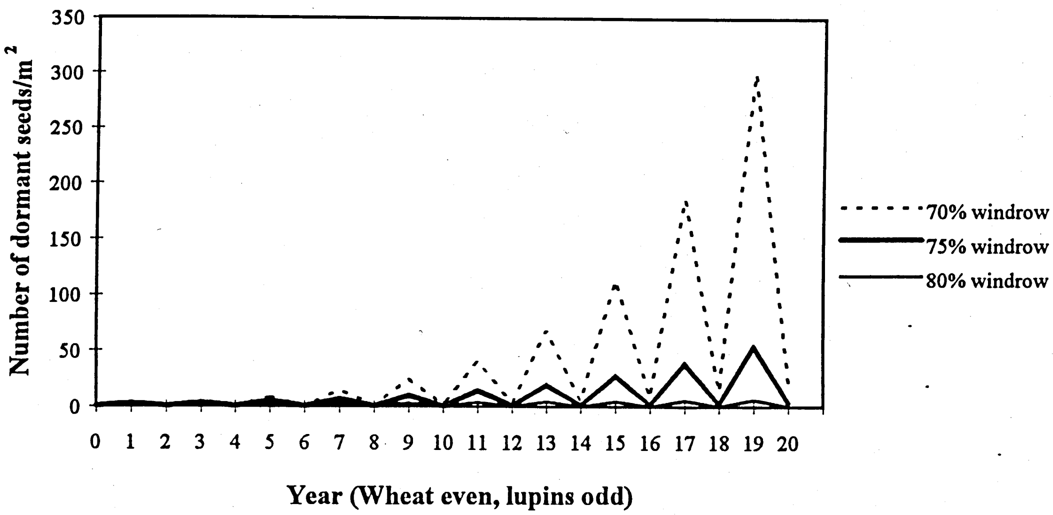
Where windrowing of wheat and lupins and the use of paraquat are all omitted, it becomes optimal to use pre-crop sprays of glyphosate in wheat and lupins, and simazine in lupins and the NPV drops to $686/ha . Likewise, if the original plant densities of 100 and 40 plants/m2 for wheat and lupins respectively are used, the NPV of scenario 3b falls from $1301 to $940. Clearly, use of paraquat for crop topping is less desirable when a glyphosate-resistant lupin is available for use in crop.

Weed control in wheat

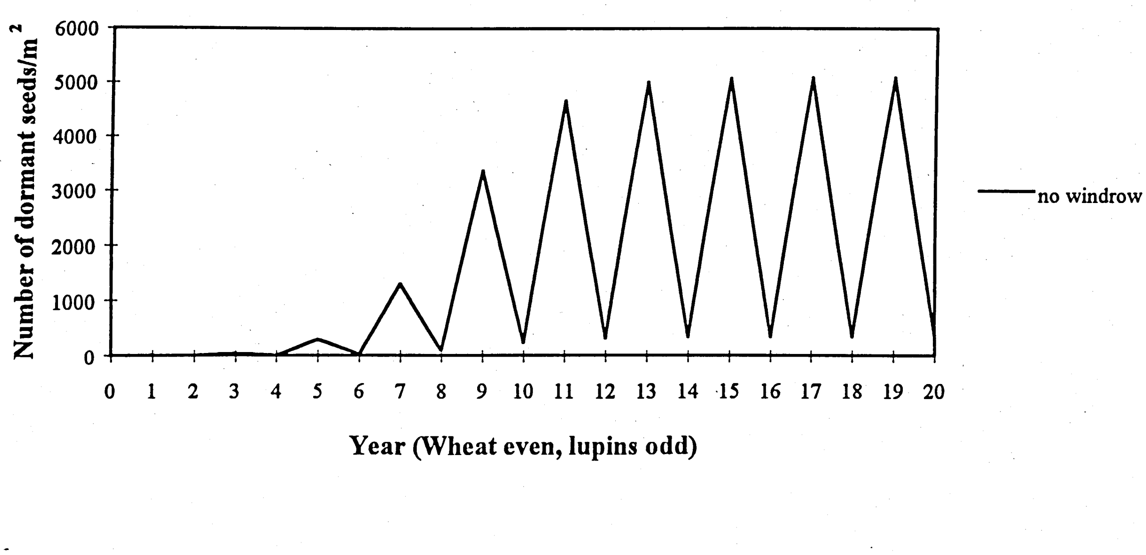
The success of a weed control strategy in the model is dependent on good ryegrass control in the wheat phase. In scenario 3a we assumed that windrowing achieves an 80 percent weed kill in wheat. The 20 percent of weeds that are not killed produce seeds which either (a) produce weeds in the next lupin crop (which are then largely controlled), or (b) remain dormant for an extra year and produce seeds in the next wheat crop. The proportion of weed seeds in category (b) is assumed to be 0.1 (Table 4) These dormant seeds have the potential to spoil an otherwise effective strategy. Even though excellent weed control is achieved in the year of lupins, the carry-through of weeds seeds from one wheat crop to the next can allow the weed population to escalate.

Figure 4 shows that the speed with which this occurs is very sensitive to the effectiveness of windrowing in wheat as a weed control measure. The three results in Figure 4 are all for the strategy which is optimal in scenario 3a, but they differ in having 80, 75 and 70 percent ryegrass control from windrowing of wheat. In all cases there is an increase in the number of dormant ryegrass seeds, but the rates of increase are very different. In the results for the 80 percent case, dormant ryegrass seeds from the last wheat crop (two seasons previously) eventually account for 68 percent of all ryegrass seeds germinating in each wheat crop. The extreme case is seen in Figure 5 where windrowing of wheat is removed, and we rely solely on ryegrass control in lupins. This sensitivity of results to the level of weed control achieved in windrowing highlights the need for further research to improve the effectiveness of the technique and our knowledge of it.

Crop Protection, C. Schmidt and D. Pannell, Figure 4.



Crop Protection, C. Schmidt and D. Pannell, Figure 5.



How much is a transgenic lupin worth?

The maximum value per hectare of a herbicide-resistant lupin is the difference in NPV between the best integrated strategies which include and exclude a herbicide-resistant lupin. The best option currently available to farmers who have a problem with herbicide resistance is the strategy for scenario 2b (NPV $985) while the best strategy including a herbicide-resistant lupin is the one for scenario 3a, which includes two in-crop applications of glyphosate to lupins (NPV $1301). Thus the potential economic value of a glyphosate-resistant lupin is NPV $316, for which the equivalent annual value is $33/ha/year. Statistics indicate that approximately 900,000 ha of lupins were grown in Western Australia in 1993-94, suggesting that the potential value of a glyphosate-resistant lupin is approximately A$30 million per year.

If the lupin has resistance only to glufosinate it provides only a small gain in profit relative to strategy 2b which employs paraquat for crop topping. Using our standard assumptions, the model suggests a total value of approximately A$1.5 million per year. However, glufosinate would prove very valuable if problems arose with strategy 2b due, for example, to residues of paraquat in the lupin seed, or development of resistance to paraquat in populations of ryegrass. The highlights the need for a system of seed testing of lupins in Western Australia, as paraquat contamination may affect the marketability of lupin grain.

Conclusion

These results indicate that the economics of transgenic lupins are complex, and while transgenic lupins hold much potential, they are not a panacea for management of herbicide resistant weeds.

In this study we assumed that the transgenic plants will yield as well as current varieties, and this may or may not eventuate. Even with this assumption, the limited effectiveness of glufosinate as a method of ryegrass control (we assumed 50 percent control after two applications of 0.5 L/ha) means that its use is only slightly more profitable than systems already in use.

While the development of a glyphosate-resistant lupin appears to have great economic value, its success depends on integrating its use with other weed management practices, such as increasing crop densities and physical removal of weed seeds. If it was possible to use glyphosate both in-crop and as a means of crop topping, then transgenic lupins would have a substantial economic advantage over current farming systems. As farmers are already using glyphosate, no new investment in machinery or education would be needed for the spraying of a transgenic lupin. Therefore the adoption of this farming system would probably be rapid.

The study emphasises the importance of non-chemical weed control methods, even when herbicide resistant crops are available. Further research is required to more accurately estimate levels of weed mortality from windrowing, increasing crop densities and other non-chemical means of weed control.

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