The role and value of herbicide resistant lupins in Western Australian agriculture

Carmel P. Schmidt and David J. Pannell

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The role and value of herbicide resistant lupins in Western Australian agriculture

Carmel P. Schmidt[A,C] and David J. Pannell[B,C]

[A]*Department of Agriculture, Western Australia, Baron-Hay Court, South Perth 6151.*
[B]*School of Agriculture, University of Western Australia, Nedlands 6009.*
[C]*Centre for Legumes in Mediterranean Agriculture, University of Western Australia.*

Abstract
Herbicide resistant weeds are having a major impact on Australian agriculture. In response to this new problem, "genetic engineering" techniques are being used to create new types of lupins which are resistant to non-selective herbicides which still kill the weeds. In this study the economic value of such a transgenic lupin was investigated using a multiperiod bioeconomic model. The model represents the wheat/lupin cropping system of Western Australia. The profitability of a wide range of weed control measures (both chemical and non-chemical) used separately and in combination with a transgenic lupin are compared with the current options available to farmers. For the scenarios considered, it is found that a system involving a Basta® resistant transgenic lupin would have similar profitability to a system based on current lupin varieties employing Gramoxone® for crop topping. However, where a transgenic lupin is resistant to glyphosate, and is used in conjunction with windrowing of both crops, farm profit increases by 33 percent.

Introduction
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 alternative major groups of selective herbicides as the predominant means of weed control is often ruled out.

Recently, the Co-operative Research Centre for Legumes in Mediterranean Agriculture (CLIMA) at the University of Western Australia has developed a transgenic Lupin (TL) that is resistant to the herbicide Basta. While this chemical is currently used for weed control in horticultural crops, it has not been used in field crops as the chemical is non- selective. The TL was developed in the hope that both ryegrass and broad leafed weeds would be controlled in lupins without damage to the crop. As herbicide resistant ryegrass poses the greatest threat to the economics of the existing farming system, this paper considers the economic impact of the TL where there exists total resistance to "Fops", "Dims" and "SUs" (different groups of chemical herbicides). These are the major groups of selective herbicides previously used to control ryegrass. While it is acknowledged that trifluralin is now taking the place of these chemicals in wheat lupin rotations, there is evidence that resistance to triflurilan is also developing in other states, and will not provide a long term solution, so will not be included in this analysis.

This paper considers the impact of using TLs under three scenarios. The first scenario places TLs in the current farming system where ryegrass resistance to Fops, Dims and SUs exists, and the farmer relies on the non-selective herbicides simazine® and glyphosate for ryegrass control. The second scenario compares the use of TLs with the strategy which integrates the best non chemical and chemical control methods. The final scenario looks at the best possible future for TLs, should transgenic resistance to a chemical such as glyphosate be developed.

The Model

Weed Growth and Control

Seeds present at the beginning of year t (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 herbicide. 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. Assumed levels of mortality from the various control measures are shown in Table 1.

Table 1. Assumed percentage weed mortalities for weed control strategies used in the model, based on limited exoerimental data.

CONTROL METHOD	Percentage weed mortality
Green manure	0.86
Cut for hay	0.67
Burn	0.61
Seed catch Lupins - Dump burnt	0.60
Seed catch Lupins - Remove dump	0.58
Cyclone Lupins - Cyclone trail burnt	0.61
Cyclone Lupins - Total burn	0.64
Windrow Lupins - windrow burnt	0.80
Windrow Lupins - seed catch	0.80
Cultivation 1 Month delay in sowing time	0.50
Cultivation - 10 days delay in sowing time	0.40
Seed catch Wheat - Dump burnt	0.60
Seed catch Wheat - Total burn	0.68
Cyclone Wheat - Cyclone trail burnt	0.61
Cyclone Wheat - Total burn	0.64
Windrow Wheat - windrow burnt	0.80
Windrow Wheat - seed catch	0.80
Simazine - full	0.60
Basta, 2 sprays (with transgenic lupin)	0.50
Glyphosate (with transgenic lupin)	0.90
Glyphosate/sprayseed at sowing	0.25
Crop top Lupins (Gramoxone® or Basta®)	0.90
Hoegrass®	0.94
Fusilade®	0.94
MCPA /Brodal	0
Glean®	0.94

Phytotoxic Damage

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

(2) $$Y = Y_o\ (1 - g)$$

where Y_o is potential yield with no weeds and no herbicide applied and g is the proportion of Y_o lost due to application of herbicide treatment. For simazine g = 0.0375, while for hoegrass g = 0.054.

Where Gramoxone is used for crop topping yield losses of either 10 or 15 percent (based on farmer and consultant experience) have been included in the model. 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 effect of competition by ryegrass on crop yield and the effect of competition by the crop on seed set of ryegrass are described by the following equation adapted from Maxwell et al. (1990).

(3) $$Y = \frac{P_1 * m * i}{a - P_1 - P_2 * k_{1,2}}$$

where P_1 is the density of the plant whose production is being considered (plants/m^2), P_2 is the density of competing plants, m is the maximum production from the plants species 1 in the absence of competition, i adjusts for the maximum yield of species 1, a is a constant, and $k_{1,2}$ controls the competitive effect of species 2 on species 1. The values for these parameters for the various types of competition in the model are given in Table 2

Table 2. Values of competition parameters for ryegrass, wheat and lupins.

P_1	P_2	units of m and y	m	a	i	$k_{1,2}$
wheat	ryegrass	tonnes/ha	2	11	1.11	0.3
lupins	ryegrass	tonnes/ha	1.2	7	1.175	0.1
ryegrass	wheat	seeds/m^2	31,000	25	-	3
ryegrass	lupins	seeds/m^2	31,000	25	-	7

We assume that a stand of lupins competes with ryegrass as effectively as does a stand of wheat despite the lower plant densities of the lupin crop usually chosen by farmers.

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

These can be divided into fixed and variable costs. In this model only the cost of the decision variables (herbicides, non-chemical control measures, harvesting and seeding rates) were considered variable. Other cropping costs such as those of fertiliser, seeding and transport were 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 hayed, in which case contract labour costs are included.

Costs of the various weed control options were estimated in detail. The estimated costs included 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 haying and green manuring and delayed sowing. Table 3 shows the estimated costs of each of the control options included in the model.

Table 3. Estimated control costs of weed control options when herbicide resistance is present

WEED CONTROL METHOD	$/ha
Green manuring	30.00
Green manuring income loss	127.60*
Hay ($/tonne)	20.00
Hay income loss	15.33*
Burning	0.00
Seed catcher (repayment and operating)	2.74
Cyclone (repayment and operating)	1.65
Windrowing (repayment and operating)	8.55
Cultivation	3.02
10 days delayed sowing	12.68*
Basta (chemical plus application)	23.00
Simazine (chemical plus application)	12.80
Glyphosate (chemical plus application)	13.60
Crop top Gramoxone (chemical plus application)	6.41
Crop top Basta (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 revenue from cropping one hectare is given by

(4) $$R = P_w\, Y - C_n - C_h - C_f$$

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.

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

(5) $$\max_{M_{ct}\, M_{nt}} \sum_{t=1}^{T} (P_w\, Y_t - C_{nt} - C_{ht} - C_f)/(1+r)^t$$

where r is the discount rate (assumed to be 8 percent). 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 values and yields	
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
1 month delayed sowing yield loss (percent)	0.23
10 days delayed sowing yield loss (percent)	0.08
Wheat hay price $/kg (incl. mowing, trans)	0.09
Lupin hay price $/kg (incl. mowing, trans)	0.07
Maximum ryegrass seed production/m^2	31,000
Initial weed density (plants/m^2)	1
Seedling mortality factor	0.2
Dormancy	0.2
Proportion viable seed carry over 2	0.6
Proportion viable seed carry over 3	0.1
Harvest index - wheat	0.32
Harvest index - lupins	0.3

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

Production costs and rates	
Super phosphate $/t	175
Rate super kg/ha (wheat)	80
Rate super kg/ha (lupins)	100
Price urea ($/t)	316
Urea kg/ha (wheat)	76
Fuel cost $/lit	0.4336
Seed dressing ($/ha) (wheat)	1.08
Seed grading & cleaning ($/ha) (wheat)	0.72
Seed, inoc (lupins) $/ha	17.6
Seed grading and cleaning (lupins) - $/ha	1
Insurance rate (wheat)	0.86 %
Insurance rate (lupins)	1.04 %
Rail freight $/t	17
Farm to bin $/t	5
Machinery r&m -direct drill $/ha	1.4
Machinery r&m -tickle $/ha	1.3
Machinery r&m - harvest $/ha	4.5
Oil, fuel and grease tickle + DD $/ha	4.032
Oil, fuel and grease direct drill, $/ha	2.311
Oil, fuel and grease - harvest, $/ha	3.345

Simplifications and Limitations
While our model is detailed in its representation 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 herbicide performance, the spatial variation in herbicide dose (Dorr and Pannell 1992) or the impact of risk aversion of the optimal management strategy. However, other published evidence indicates that the impacts of risk on optimal management strategies for ryegrass are small (e.g. Pannell 1990; 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 MCPA, Sprayseed, glyphosate and Brodal. 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).

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 5) and the mortality values assumed for different control measures.

Results

Results presented are for a wheat/lupin rotation in 10 different scenarios (Table 6). The following sections describe each of these scenarios in more detail.

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

	Scenario Description[1]	NPV[2]	Annuity[2]	Final weed Density[3]
1a	Conventional practice, no HR	1010	103	–
1b	Conventional practice, with HR	-573	-58	9213
1c	1a with HR , Basta in-crop & crop topping	-462	-47	3643
2a	Increased plant densities, delayed sowing	250	25	538
2b	Increased plant densities, Gramoxone crop topping	985	100	19.7
2c	2b no Gramoxone, Basta in-crop & crop topping	1001	102	6.04
2d	2b no Gramoxone, Basta crop topping only	926	94	19.7
3a	2b no Gramoxone, 1 in-crop gylphosate spray	1150	117	19.7
3b	2b no Gramoxone, 2 in-crop glyphosate sprays	1301	133	0.36
3c	3b windrowing lupins replaced by crop topping	1206	123	0.06
3d	3b 3 in-crop glyphosate sprays	1235	126	0.01

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

Scenario 1a.

In the conventional farming system, where HR did not exist, farmers relied on a combination of chemicals to control ryegrass. In this model glyphosate, simazine, Glean and Fusilade are used for grass control, while MCPA and Brodal are used for broad leaf control. Assuming (unrealistically) that HR does not develop, the NPV over 20 years using this scenario is $1010/ha (Table 6).

Scenario 1b

Once HR is introduced into the system, Glean and Fusilade are no longer options and the farmer's profit falls to -$573/ha. Obviously, given this negative return, farming would cease.

Scenario 1c

If we introduce a TL into the rotation, and use 2 in-crop sprays of Basta and one "crop top" using Basta, the net return to the farmer worsens to -$462/ha. Thus TL's alone are not a solution to the HR problem (Table 6).

Scenario 2a

In this scenario, the farmer decides to use a combination of methods to combat ryegrass without using the TL. The simplest and most cost effective method is to increase the number of wheat plants/m^2 from 100 to 200. As well as this the best strategy includes increasing the lupin plant density from 40 to 60 plants/m^2, delaying sowing of both wheat and lupins and windrowing both crops prior to harvest. With these methods the NPV is $250/ha (Table 6).

Scenario 2b

Although not yet registered, very many farmers in Western Australia are considering using Gramoxone for "crop topping" in lupins. 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. Even so, when scenario 2a is combined with crop topping assuming a 10 percent yield loss, the farmer's NPV increases to $985/ha, which is within $25 of the original return before development of HR (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 Gramoxone causes 15 percent loss, the NPV drops to $940/ha.

Scenario 2c

Where it is possible to use Basta (again using 2 in-crop sprays and one crop top) and the TL in conjunction with the same windrowing and increased plant densities methods of weed control used in scenario 2b, it is no longer necessary to use Brodal, nor economic to use glyphosate in wheat and lupins. The resulting NPV is $1001/ha, i.e. slightly higher than that achieved where Gramoxone is used with 10 percent yield loss (Table 6). This is based on the assumption of no phytotoxic yield loss in the TL due to Basta. If yield loss when using the TL and Basta were actually 10 percent (as for Gramoxone), the NPV would fall to $909/ha, i.e. less than when using Gramoxone.

In the above examples, Gramoxone is used only once (for crop topping) while Basta is used 3 times, twice as an in-crop spray and once for spray topping. An explanation of the lower returns for scenario 2b (using Gramoxone) is the high cost of using Brodal for broad leaf weed control, without obtaining any control of ryegrass. In contrast, Basta controls both ryegrass and broad leaf weeds in scenario 2c (Table 7).

Table 7. Cost of chemical control options.

Chemical	$/ha
Basta 2 in-crop sprays	20.00
Basta 1 crop top	30.00
Glyphosate 1 in-crop spray	10.60
Gramoxone 1 crop top	3.41
Brodal	12.44

Scenario 2d

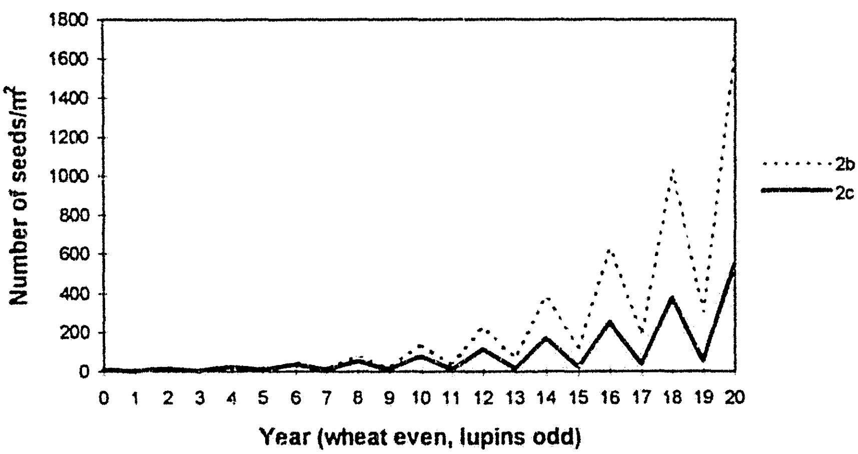
If Basta is used only for crop topping and not as an in-crop spray, it becomes necessary to again use Brodal in lupins and optimal to use glyphosate in wheat. However this change is not economic, reducing the NPV to $926/ha (Table 6). This option would only be realistic if farmers expected yield losses of more than 15 percent when using Gramoxone (scenario 2b), and phytotoxic damage of around four percent from in-crop use of Basta.

If the farmer has good weed control from using MCPA in wheat and does not require either Brodal or an in-crop spray of Basta, the NPV for scenario 2c rises to $1005/ha However this is less than the $1063/ha achieved when Brodal is removed from scenario 2b.

Seed numbers

Figure 1 shows the effect of the two best strategies so far (2b not using a transgenic lupin and 2c using a transgenic lupin) on ryegrass seed numbers produced each year over the 20 year period. As weed control in the lupin phase in scenario 2b is poorer than in 2c, a greater number of weed seeds are produced in this phase each year, which in turn are carried into the wheat.

Figure 1. The effect of weed control strategies 2b and 2c on the number of ryegrass seeds produced in wheat and lupin crops over a 20 year period.



Scenario 3a

In scenarios 2a, b, c and d it was assumed that the yield of TL lupins was as high as that of the current lupin varieties. In this scenario (3a), we continue to assume these yields, and 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 also assume that this herbicide has no effect on grain yield of the TL, then substituting crop topping with Gramoxone in scenario 2a for one in-crop spray with glyphosate results in an NPV of $1150/ha (Table 6).

The reasons for this increase in NPV are (1) avoidance of yield loss which occurs with crop topping, (2) a cost saving since we no longer have to use Brodal for broad leaf control (as glyphosate will control these weeds), nor glyphosate as a pre-crop spray in lupins and (3)glyphosate as an in-crop spray kills weeds earlier in the growing season thereby reducing the duration of competition with the crop.

Scenario 3b

The best results come from the use of two glyphosate sprays in-crop, the same high plant densities and windrowing of both wheat and lupin crops (as used in scenario 2a), and the use of no other herbicides, giving an NPV of $1301 (Table 6). Clearly the benefits of this TL are substantial, even in circumstances where there is no HR. Should yield losses of 10 percent per spray occur the NPV falls in scenario 3b to $1204, which is still significantly more profitable than existing technologies.

Scenario 3c

Where yields are maintained, but windrowing of lupins in scenario 3b is replaced by crop topping using Gramoxone, the NPV drops to $1206. If windrowing of both wheat and lupins is omitted while using Gramoxone for crop topping, the NPV falls to $820, and it is optimal to use a pre-crop spray of gylphosate in wheat.

Where windrowing of wheat and lupins and the use of Gramoxone are all omitted, the NPV drops to $686/ha and it becomes optimal to use pre-crop sprays of glyphosate in wheat and lupins, and simazine in lupins. 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.

Scenario 3d

Increasing the number of glyphosate sprays from two to three in the best scenario 3b drops the 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.

Weed control in wheat

The success of a transgenic lupin is dependent on good ryegrass control in the wheat phase. In scenario 3b we assumed that windrowing achieved an 80 percent weed kill in wheat. The 20 percent of weeds that weren't killed either 1) set seed which produced weeds in the next lupin crop (which where then controlled), or 2) remained dormant until the next wheat crop when they produce weeds. It is this percentage of dormant seeds which have the potential to cause the greatest yield losses in wheat.

Figure 2 shows the build up of dormant seeds in scenario 3b, with 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, however, the rate at which this happens is dependent on the success of windrowing. The dormant seeds germinate in the following wheat crop, compete with it, and reduce wheat yield. As windrowing of wheat occurs at the end of the season it has no effect on ryegrass competition. Dormant ryegrass seeds eventually account for approximately 68 percent of all viable ryegrass seeds in wheat.

The extreme case is seen in Figure 3 where windrowing of wheat is removed, and we rely solely on ryegrass control in lupins.

Figure 2. The effect of varying the percentage weed control achieved by windrowing of wheat in scenario 3b, on the number of dormant ryegrass seeds in wheat and lupin crops over a 20 year period.

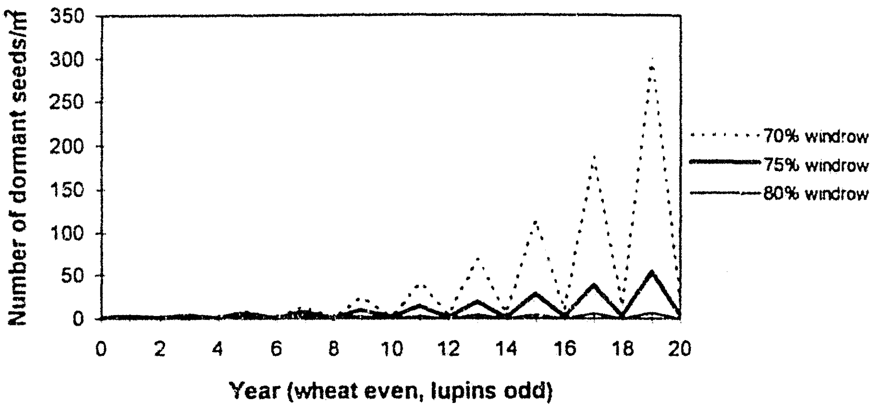
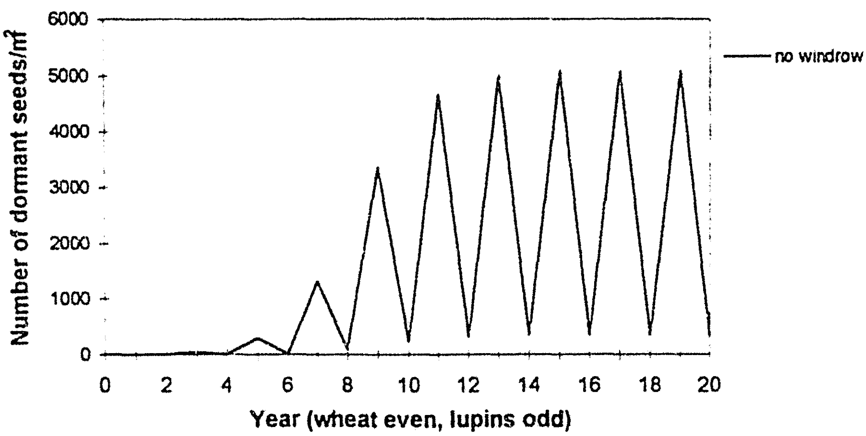


Figure 3. The effect of removing windrowing in wheat from weed control strategies 3b on the number of dormant ryegrass seeds in wheat and lupin crops over a 20 year period.



How much is a transgenic lupin worth?

The maximum value per hectare of a transgenic lupin in this model is the difference between the best option currently available to farmers where herbicide resistance is present, (scenario 2b, NPV $985) and the use of two sprays of glyphosate when using a glyphosate resistant lupin (scenario 3b, NPV $1301), i.e. NPV $316, or annuity of $33/ha/year. Statistics indicate that approximately 900,000 ha of Lupins were grown in W.A. in the 1993-94 year, suggesting the potential value of a glyphosate TL is approximately $30 million per year

If the TL lupin has resistance only to Basta it provides no real gain in profit relative to strategy 2b which relies on crop topping. Nevertheless, our analysis has shown that a Basta resistant TL is of similar profitability to the best current strategy. If problems arose with strategy 2b due to chemical residues or development of herbicide resistance to Gramoxone by ryegrass, a Basta resistant TL would be very valuable. The study highlights the need for a system of seed testing of lupins, as Gramoxone contamination may affect their export potential

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 herbicide resistance

Early results from trials with Basta indicate that it is only partially effective as an in-crop spray for ryegrass. In this model we assumed a 50 percent weed kill as the combined result of two 0.5L/ha sprays. However single spray rates of up to 3 L/ha have also shown only 50 percent kill. We also assume that the transgenic plants will yield as well as the current varieties which may or may not eventuate. Thus, even when the yield of transgenic lupins is equal to current varieties, the effectiveness of Basta as a method of ryegrass control makes its use of similar profitability to systems already in use.

The model also emphasises the importance of non-chemical weed control methods. Further research is required to determine more accurate weed control figures for windrowing and increasing crop densities. The effect of crop/Basta interaction must also be studied to determine the impact of crop competition and Basta efficacy on grain yield.

While the development of a glyphosate-resistant lupin has the greatest economic value, it is again dependent on plant densities and non-chemical weed control methods, indicating that good farming practices are essential for its success. 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 be extremely rapid.

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