The Value of Green Manuring in the Integrated Management of Herbicide-Resistant Annual Ryegrass (*Lolium rigidum*)

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ABSTRACT

Herbicide resistance has become a major problem in Australian dryland agriculture. This situation has resulted from the repeated use of herbicides in place of the traditional weed control provided by cultivation and grazing. Farmers have addressed the problem of herbicide resistance by adopting a system of integrated weed management that allows weed control with a range of different techniques and herbicides. One of the non-chemical methods being considered by farmers is “green manuring”, which involves ploughing a healthy growing crop or pasture into the soil in order to prevent weed seed production and provide other benefits. In this study, the trade-offs between the effective weed control and biological benefits provided by green manuring and the large short-term economic losses associated with this practice are investigated for various rotations and patterns of herbicide use. This analysis is conducted using RIM, a bio-economic management model for ryegrass (*Lolium rigidum*).

INTRODUCTION

Herbicide resistance has become a major problem in Australian dryland cropping, following the widespread and persistent use of herbicides for weed control. Contributing factors include the adoption of minimum and no-tillage systems, and reduced areas of pasture in favour of continuous cropping rotations. Repeated application of herbicides without the traditional weed control provided by cultivation and grazing has led to a high selection pressure on weed species (Powles *et al*., 1997). This particularly applies to annual ryegrass (*Lolium rigidum*) which, given its characteristics, has developed multiple resistance to a wide range of commonly used selective herbicides (Powles and Holtum, 1990; Powles and Matthews, 1991; Gill *et al*., 1994; Gill, 1997, Powles, 1997).

Farmers have addressed the problem of herbicide resistance by adopting a system of integrated weed management that allows weed control with a range of different techniques, including herbicides (Combellack and Friesen, 1992; Powles *et al*., 1997). One of these non-chemical methods is “green manuring”, which involves ploughing a healthy growing crop or pasture into the soil. Green manuring provides highly effective weed control, increased nutrient availability in the following year, and improved soil organic matter. On the other hand, the loss of a year’s production involves a short-term economic sacrifice.

In this study, we evaluate the value of green manuring within an integrated ryegrass management system. In particular, we investigate the relationship between the current ryegrass infestation and the long-term financial value of green manuring. We focus on two specific questions: (a) how large does the annual ryegrass seed bank need to be before it is worth green manuring lupins? and (b) how do the key biological and economic variables affect this break-even weed density? We start with the hypothesis that green manuring only pays off when weed seed bank numbers are particularly high. We also evaluate the effect of alternative practices (e.g. pasture) on the value of green manuring. A second hypothesis tested is that a green manuring year needs to be preceded and followed by effective weed control measures in order for the investment in green manuring to be justified. The analysis is conducted using RIM (Pannell *et al*., 1999), a bio-economic model representing ryegrass population dynamics, competition, a wide range of weed treatment options and financial details over a 20-year period. A number of sensitivity analyses were carried out for different rotations, patterns of resistance to selective herbicides (Group A and B), initial seed bank numbers, weed control in the year prior to green manuring, control levels of green manuring, proportion of germination and weed-free wheat yields.

MODEL DESCRIPTION

RIM (Ryegrass Integrated Management) is a bio-economic model that simulates the dynamics of a ryegrass population over a 20 year period (Pannell *et al*., 1999). It is a decision support tool designed specifically for the evaluation of various management strategies to manage herbicide-resistant weeds in dryland agriculture. The model includes a detailed representation of the biology of weed, crops and pasture as well as of the economics of agricultural production and management.

Weed biology

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

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

Where

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

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

Enterprises

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

Control methods

With the RIM model there is a wide range of chemical and non-chemical control options available:

- Selective herbicides (toxic to certain weeds, but not to certain crops) provide very effective weed control, but result in a strong selection pressure for resistance when applied continuously (Powles, 1997).
- Non-selective herbicides (toxic to both weed and crop plants). In spite of their widespread application, there are only relatively few cases reported of resistance to non-selective herbicides. Powles *et al.* (1997) suggest that this is an indication that resistance gene frequencies for such herbicides are low.
- Non-chemical methods include anything other than using chemicals, varying from cultivation and delayed sowing to seed catching and stubble burning. Grazing during a pasture phase is another important non-chemical option. Heavily weed-infested crops or pasture can be cut for hay/silage or used for green manuring.

Each control strategy has its own impact on weed mortality and seed set, as shown in Table 1. However, Gorddard *et al*. (1996), Matthews (1996), Schmidt and Pannell (1996a), Gill and Holmes (1997), and Powles *et al*. (1997) suggest that no one method available provides the optimal management strategy for herbicide-resistant weeds. Instead, only a combination of a wide range of weed control methods can achieve very effective and sustainable weed control. Because control methods are conducted at different times, their combined impacts are considered to be multiplicative rather than additive (Pannell *et al*., 1999)[1].

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

Table 1. Weed control methods and percent reduction in current ryegrass plants or seed numbers for some treatments used in the model (dashes mean that this treatment is not an option for this enterprise). The letters between brackets after each herbicide name indicate the herbicide mode-of-action groups.

Weed control methods	Wheat	Barley	Canola	Lupins	Legume Pasture
Knockdown with glyphosate (M)	97%	97%	97%	97%	_
Trifluralin (D)	70%	70%	70%	70%	_
Simazine® (C)	_	_	75%	75%	10%
Atrazine (C)	_	_	75%	_	_
Glean® pre-emergence (B)	75%	_	_	_	_
Hoegrass® (A)	95%	95%	95%	95%	_
Tickle, wait 10 days, seed	5%	5%	5%	5%	_
Tickle, wait 20 days, seed	5%	5%	5%	5%	_
Year-round grazing	_	_	_	_	*
High intensity grazing in spring	_	_	_	_	**
Paraquat-top lupins/pasture(L)	_	_	_	80%	85%
Green manuring	98%	98%	98%	98%	98%
Cutting for hay + glyphosate (M)	95%	95%	95%	95%	95%
Cutting for silage + glyphosate	98%	98%	98%	98%	98%
Swathing	_	25%	20%	20%	_
Mowing pasture	_	_	_	_	98%
Seed catching - burn dumps	60%	60%	60%	60%	_
Seed catching – total burn	68%	68%	68%	68%	_
Windrowing – burn windrow	50%	50%	50%	50%	_
Windrowing – total burn	70%	70%	70%	70%	_
Burning of stubbles/pasture residues	30%	30%	30%	30%	20%

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

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

Economic values

The model calculates costs, revenues, profit and net present value. Costs associated with cropping, pasture and various weed control options have been estimated in detail. They account for costs of input purchasing; costs of machinery operating, maintenance and repayment; costs of contracting of labour for hay and silage making; and costs of crop insurance. There are also costs of crop yield penalty due to practices such as green manuring and delayed sowing. Environmental costs associated with some non-chemical methods such as cultivation and burning are also represented in the model. Economic returns from crops and stock are based on grain and wool sale prices. Sheep value is given as a gross margin per DSE. Following Gorddard *et al.* (1996), annual net profit from cropping one hectare is given by:

$$R = P_w \,.\, Y - C_n - C_h - C_f \qquad (2)$$

Where

R = Annual net profit

P_w = Crop sale price

Y = Crop yield

C_n = Cost of non-chemical control
C_h = Cost of herbicides
C_f = Fixed costs (fertilizers, transport)

Because the model is run over 20 years time (*T*), annual net profit must be discounted to make them comparable to the start of the period. Refer to Pannell et al. (1999) for a description of the discounting procedure used to calculate the net present value (*NPV*) of profit.

Model limitations

RIM is a deterministic model, meaning that it does not allow for the year-to-year variation in growth, herbicide performance, prices or other variables (Dorr and Pannell, 1992). Instead, it is assumed that all years are identical (constant climate) in terms of their potential production, although the weed population varies over time and affects yield accordingly (Pannell *et al*., 1999). The model does not optimize, but is used to simulate a wide range of potential treatment strategies, so that an overall strategy which is at least near-optimal can be identified. All weeds other than ryegrass are assumed to be adequately controlled. There are also limitations regarding some data and estimated parameters used in the model. They are based on experimental data where possible, but a number have had to be estimated subjectively, in consultation with scientists and extension agents.

CONTROL STRATEGIES

Rotations

The value of green manuring was investigated for three sequences of enterprises examined over 20 years:

1. a continuous cropping wheat/wheat/lupin rotation (WWL),
2. a continuous cropping wheat/lupin/wheat/canola rotation (WLWC), allowing for a more diverse range of cropping enterprises,
3. a wheat/wheat/lupin rotation punctuated by a 3-year phase of cadiz serradella pasture in years 14 to 16.

This analysis examines the value of green manuring when practiced in the second year of the rotations. The focus on year two of the rotation aims at capturing the effect of different initial seed bank numbers on the value of green manuring, as well as of any change in weed control strategies around the green manuring phase. The main rotation examined is wheat/wheat/lupin (WWL), with the wheat/lupin/wheat/canola (WLWC) rotation used to investigate the value of green manuring in a more diverse cropping rotation. The fact that lupins grain is less valuable than wheat or canola, and that vegetative lupins considerably improve soil fertility, means that lupins are better suited for green manuring than the other crops. Therefore, rotations have been rearranged in such a way that lupins are always the green manured crop in year two of the rotation.

The pasture phase was investigated in the scenario of fully developed resistance to selective herbicides, because it provides an alternative to the more radical approach of green manuring. A three-year pasture phase allows for high levels of weed control without the use of selective herbicides, so this is likely to diminish the value of green manuring relative to an analysis based only on continuous cropping. Although in preliminary model runs a pasture phase of different lengths and species was evaluated in different years of this WWL rotation, the most profitable strategy including a pasture turned out to be a three-year cadiz serradella pasture phase in years 14 to 16 of the rotation.

Herbicide use

Three scenarios of herbicide use and herbicide resistance were defined. The first scenario was full resistance to selective herbicides of mode-of-action Group A and B (meaning that no applications of these chemical groups remain available). In the second scenario it was assumed that there were two uses of herbicides of Group A (e.g. Hoegrass®, Fusilade®) and two of Group B (e.g. Glean®, Logran®) left available before complete herbicide resistance developed. Scenario three had six applications of each chemical group available. In all three scenarios it was assumed that there were four applications left of herbicide of Group C (e.g. Simazine®, atrazine), four of Group D (trifluralin), 15 of Group M (glyphosate) and 15 of Group L (paraquat).

The simplifying assumption was made that after these defined numbers of uses, resistance to that chemical group appears suddenly and completely. Although this is not always strictly accurate, resistance does frequently go from low to very high levels in a period as short as one or two years (after several years of herbicide use) (Tardif *et al*., 1993; Powles *et al*., 1997).

The three scenarios of herbicide resistance were run for both continuous cropping rotations. The pasture phase was investigated only in the scenario of fully developed resistance to selective herbicides of Group A and B. In every situation the model was run with and without green manuring in year two (lupins).

Non-chemical methods

Complementing these strategies of green manuring and herbicide application, many combinations of other control methods (non-chemical and non-selective herbicides) were investigated in order to find the most profitable integrated strategies of weed management. In general, these strategies included high crop seeding rates and, in some years, delayed times of seeding for wheat plus knockdown herbicide glyphosate (Group M) and tickle. Seeding was normally not delayed for lupins, consistent with usual farmer practice. However, delaying the seeding of lupins 20 days preceded by a glyphosate-knockdown and a tickle-cultivation proved profitable in the green manuring phase. Crop-topping lupins with the non-selective herbicide paraquat and spraying pasture with glyphosate before weed seed set proved to be profitable in the long run. Although sustainable grazing is recommended during the first year of pasture for good pasture establishment (Nutt and Paterson, 1997), the last two years were grazed intensively in spring and early winter to obtain good weed control. Canola was always swathed and windrowed. Seed catching or windrowing combined with burning of dumps/windrows or with total burn were often attractive control methods during crop harvest. Pasture residues were burnt during the last year of the pasture phase, previous to cropping.

SENSITIVITY ANALYSES

Parameters of the model are subject to uncertainty or to change over time, so a sensitivity analysis on a several key parameters was conducted. Following Pannell's (1997) approach to sensitivity analysis (Strategy A), a number of parameters, which are uncertain or subject to change, were identified and the most likely values for each parameter were selected.

As the value of green manuring is likely to depend on the severity of ryegrass infestation, we varied the initial ryegrass seed bank numbers. A sensitivity analysis was run on this parameter for the values 100, 200, 400, 800 and 1600 seeds m^{-2}. In order to investigate the impact of early weed control on the overall strategy, a series of model runs were carried out for a range of weed control levels in year one (40, 50, 60, 70, 80, 90, 95, 98, 99, 99.9 percent). Also, several levels of effectiveness of green manuring were tested. In addition to the model default value of 98 percent, all scenarios were tested assuming 90, 95 and 100 percent reduction in weed seed production. Given the importance of germination in a green manuring analysis, a brief sensitivity analysis on the seed bank decline was also conducted. In this case, the default value of about 80 percent was changed to 70 and 90 percent in the scenario of total resistance to herbicide Group A and B for the WWL rotation. Finally, for the scenario of no herbicides from Group A or B and the WWL rotation, the model was run with a higher weed-free yield, increased by 23 percent for all rotations, (e.g. yield following a lupin crop was increased from 1.7 to 2.1 t ha^{-1}).

RESULTS AND DISCUSSION

Research to address the question: " What difference does green manuring make?" involved the simulation of the most profitable weed management strategy found, with and without green manuring. We start now by following the example of a scenario with a standard WWL rotation, no use of Group A and B herbicides possible due to resistance, and with an initial ryegrass infestation of seed bank numbers of 800 seeds m^{-2}. The range of IWM methods employed for this strategy in the RIM analysis is shown in Table 2.

Table2. Weed management strategy used in the scenario of a WWL rotation, full resistance to Group A and B herbicides, initial ryegrass seed bank with 800 seeds m^{-2}, with and without green manuring.

Treatments	No green manuring	Green manuring
Knockdown –glyphosate	Years: 1, 3, 4, 6, 7, 9, 10, 12, 13, 15, 16, 17, 18, 19	Same years + year 2 (lupins)
Trifluralin	Years: 1, 3, 7, 14	Same years
Simazine® pre-emergent	Lupin years: 2, 5, 8, 11	Same years
High crop seeding rate	All years	All years
Tickle+20-day delayed seeding	Years: 1, 3, 4, 6, 7, 9, 10, 12, 13, 15, 16, 17, 18, 19	Same years + year 2 (lupins)
Paraquat crop-topping	Lupin years: 2, 5, 8, 11, 14, 17	Same years, no year 2 (lupins)
Green manuring	—	Year 2 (lupins)
Seed catch-burn dump	Years: 7, 10, 13, 16, 19	Same years
Seed catch-total burn	Years: 6, 8, 9, 12, 15, 17, 18	Same years
Windrowing-burn windrow	Years: 1, 4	Same years
Windrowing-total burn	Years: 2, 3, 5, 11, 14	Same years, no year 2 (lupins)

In both cases, the weed management strategy remained relatively constant with and without green manuring. Only minor differences in other years were found between the strategies including and excluding the practice of green manuring. An exception, however, was an application of glyphosate followed by a tickle and a 20-day delay seeding for lupins in the second year (obviously, crop-topping with paraquat and windrowing were not practiced in the green manuring year).

Table 3. Variation in gross margin and ryegrass plant density over 20 years for two weed management strategies, with and without green manuring.

Years	Gross margins ($/ha/yr)		Ryegrass plants/m^2 (November)	
	No green manuring	Green manuring	No green manuring	Green manuring
1	140	140	16	16
2	-16	-139	8	0
3	138	165	16	4
4	125	128	16	4
5	-12	-3	12	3
6	148	154	26	7
7	93	99	33	9
8	-21	-12	13	3
9	149	154	24	7
10	113	118	33	9
11	-18	-6	20	6
12	144	152	41	13
13	108	116	55	18
14	-21	-5	35	12
15	138	148	66	27
16	102	112	87	36
17	-43	-34	28	12
18	138	147	66	32
19	102	111	87	43
20	-2	11	621	316

The results of the model showing variation in gross margin and ryegrass plant infestation over 20 years for each strategy are presented in Table 3. A comparison of the two strategies indicates a similar trend in ryegrass numbers in both, although the effect of the green manuring control effectiveness is evident over the following years (the ryegrass density level is kept always below 100 seeds m^{-2}). Another obvious difference is that the gross margins are slightly higher after lupins have been green manured in year two of the rotation. The increase in gross margin is particularly marked (about \$40 ha^{-1} yr^{-1}) in the first year following the green manuring phase. Negative gross margins are found in every year that is lupins (5, 8, 11, 14, 17, 20) in both cases, except, of course, the gross margin is much lower in the year that lupin is green manured.

The information presented above corresponds only to a single result for one scenario. This procedure was repeated for different starting seed bank numbers. In turn, the whole set of model runs was then carried out for various scenarios of herbicide application (two and six shots left of Group A and B) and again for a more diverse cropping rotation (WLWC).

Net value of green manuring

Table 4 shows the annuities for various scenarios of initial ryegrass seed bank numbers and herbicide resistance on the two continuous cropping rotations, WWL and WLWC.

Table 4. Net value of green manuring as affect by herbicide use, initial ryegrass seed bank numbers and green manuring for two different cropping rotations. (Full results on Table 1A of the Appendix).

		WWL	WLWC
Ability to use Group A & B herb. due to resistance (no. of applications)	Initial ryegrass seed bank (seeds m^{-2})	Net value of green manuring (\$/ha/yr)	Net value of green manuring (\$/ha/yr)
0	100	-1	0
0	200	1	1
0	400	2	2
0	800	3	4
0	1600	3	4
2	100	-5	-4
2	200	-3	-3
2	400	-1	-3
2	800	1	-2
2	1600	2	0
6	100	-7	-9
6	200	-6	-8
6	400	-4	-7
6	800	-1	-6
6	1600	1	-5

This analysis reveals that the value of green manuring varies significantly between scenarios. In some cases, it is a valuable tool, while in others it detracts significantly from profitability. It is therefore important to understand the circumstances under which green manuring is an economically beneficial option.

Firstly, it is clear that, within the range of weed seed bank numbers considered here, the value of green manuring generally increases the higher the ryegrass infestation. However, these results are followed up by a specific analysis (below) on the impact of weed control in year one.

As would be expected, there is no value for green manuring where herbicides remain effective (no resistance). It appears that green manuring will not be an economic option while any Group A or B herbicides remain effective (unless weed densities somehow reach very high levels despite the effectiveness of those herbicides).

Another interesting observation is that the relative value of green manuring is different for the two cropping rotations, according to the level of herbicide use. As shown in Table 4, when herbicides of Group A and B cannot be used due to resistance, green manuring appears to be slightly more beneficial for the WLWC rotation. In the situation where two applications of herbicides of Group A and B are possible, the value of green manuring is higher or equal for the WLWC rotation at low seed bank numbers (100 and 200 seeds m^{-2}) and higher for the WWL rotation at high seed bank numbers (400, 800 and 1600 seeds m^{-2}). For the scenario where six shots of selective herbicides can be used, the value of green manuring is always higher for the WWL rotation. In conclusion, green manuring is only profitable in the more diverse rotation where considerable resistance exists.

Our original hypothesis also predicted that the practice of green manuring would increase the use of highly effective control methods around that year. Although no major differences were found in other years, in this phase, delaying the sowing of lupins by 20 days (preceded by the use of a glyphosate-knockdown and a tickle) before green manuring this crop proved profitable. A sensitivity analysis on the weed percent kill in the first year follows to help explore these results further.

Weed control prior to green manuring

The effectiveness of green manuring in reducing the ryegrass seed bank is likely to be influenced by management in the preceding and following year. In order to investigate that, a sensitivity analysis was conducted on the percent kill obtained in year one as to find out whether and how it affected the performance of green manuring in year two. For the purpose of simplification of the analysis, only two control methods were selected and their combined control percent worked out. At seeding of the crop, at least 5 percent of the germinating ryegrass seeds are killed during the seeding operation by default (seeding at first chance). This method was complemented with an application of the Group B herbicide trifluralin, which control level was then changed (for wheat only) to add up to the desired total weed control on wheat in year one. The other three applications of trifluralin were used in lupins so that the change in percent control would not affect the rest of the strategy. The model was thus run with a series of weed control levels on the first year (40, 50, 60, 70, 80, 90, 95, 98, 99, 99.9

percent). This was done for a starting ryegrass seed density of 1600 seeds m^{-2} and for a WWL rotation with no availability of herbicides of Group A and B.

Table 5. Net value of green manuring as affect by weed control in the year prior to green manuring and seed bank numbers in year two of the rotation, with a starting ryegrass seed density of 1600 m^{-2} for a scenario of full resistance to herbicides of Group A and B in a WWL rotation. (Full results on Table 2A of the Appendix).

Weed control in year 1 of the rotation (%)	Net value of green manuring ($/ha/yr)	Ryegrass seed bank numbers in year 2 (seed/m^2)
40	-1	10701
50	0	10131
60	0	9360
70	0	8480
80	0	7226
90	1	5694
95	2	4507
98	2	3811
99	3	3561
99.9	2	3328

From the results shown in Table 5 and the trends illustrated in Figures 1 and 2, it can be concluded that, generally, the more effective the weed control applied in the first year, the higher the value of green manuring in the second year. Despite being a costly practice, and hence generally more attractive when more weeds are present, green manuring is even more useful in conjunction with very effective weed control in the year before. Excellent weed control followed by a green manuring phase drives the seed bank to a very low level, which is likely to remain so for a much longer period of time.

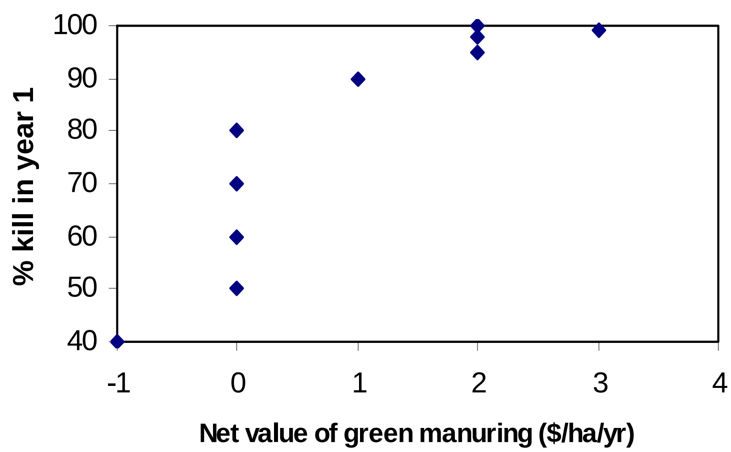

Figure 1. Effect of weed control in year one on the net value of green manuring.

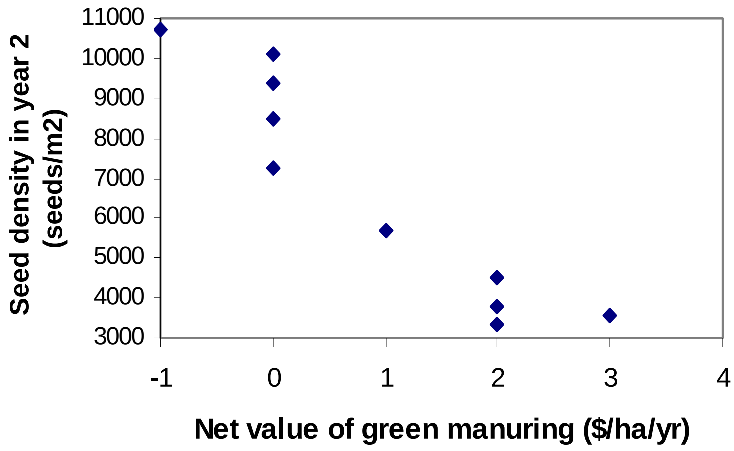

Figure 2. Effect of ryegrass seed bank numbers at the start of year two on the net value of green manuring.

Efficacy of green manuring

In order to investigate the impact of the level of ryegrass control achieved by green manuring on the economic benefits of this method, the model was run with 90, 95 and 100 green manuring control percent, next to the default value of 98 percent. This sensitivity analysis was conducted for a WWL rotation under a scenario of full resistance to herbicides of Group A and B.

Table 6. Effect of various green manuring control levels on annuity ($/ha/year) under different initial ryegrass seed bank numbers for a scenario of full resistance to herbicides of Group A and B in a WWL rotation.

Initial ryegrass seed bank (seeds m^{-2})	Ryegrass seed production control achieved by green manuring				
	No	90%	95%	98%	100%
100	81	75	78	80	83
200	76	71	74	77	80
400	70	65	69	72	76
800	64	60	64	67	71
1600	58	54	58	61	65

The results in Table 6 show a consistent increase in annuity as the control level of green manuring goes up for all initial seed bank numbers. This fact confirms the expectation that green manuring, as an expensive practice, generally has to be highly effective to be economically worthwhile.

Also interesting is that the break-even value of weed control falls as ryegrass seed bank numbers increase. With 100 seeds m^{-2} initially in the soil, the control level of green manuring must be above 98 percent to be as well off with green manuring as without it. The control level of green manuring decreases gradually to 95 percent at the highest starting ryegrass seed density in order for green manuring to be profitable.

Although the model default value of 98 percent for green manuring control is considered acceptable, the results of this analysis indicate that any variation in this value has a significant impact on the outcome of the model and thus on the choice of management strategies for annual ryegrass.

Seed bank decline

A sensitivity analysis was conducted on the level of ryegrass seed decline in the system. The same scenarios of initial seed bank numbers, with and without green manuring, for the two continuous cropping rotations under full resistance to herbicides of Group A and B were simulated for 70 and 90 percent of ryegrass germination.

In RIM, annual ryegrass germinates according to a pattern of five consecutive cohorts. The model default value of about 80 percent of total annual germination is the sum of five cohorts: 5, 38, 23, 14 and 2 percent. These proportions of the total germination are represented in the model by the correspondent germination of the seed remaining in the seed bank (5, 40, 40, 40 and 10 percent). For 70 percent germination, the remaining seed germinating in cohorts is 4, 33, 32, 27 and 5 percent, and for 90 percent germination, it is 5, 44, 48, 56 and 18 percent.

Table 7. Net value of green manuring as affect by ryegrass germination and initial ryegrass seed bank numbers, for two different cropping rotations. (Full results on Table 3A of the Appendix).

Ryegrass seed germination (%)	Starting ryegrass seed bank numbers (seeds/m2)	WWL Net value of green manuring ($/ha/yr)	WLWC Net value of Green manuring ($/ha/yr)
70	100	-4	-2
70	200	-1	-1
70	400	0	0
70	800	2	1
70	1600	2	1
90	100	2	1
90	200	3	2
90	400	4	4
90	800	4	5
90	1600	5	5

When comparing Table 7 with the scenario of full resistance (0 shots left) of Table 4, it can be seen that, in both rotations, the net value of green manuring increases with higher initial seed bank numbers and as the proportion of germination goes up. An explanation for this fact is that a radical control method such as green manuring becomes more attractive as weed numbers increase in the system. Also, at higher germination, more weeds are available to be killed by the green manuring operation. Fewer weeds escape being killed by hiding away in the seed bank.

Weed-free yield

The weed-free yields of crops are important parameters of the model, although they are also prone to change or uncertainty. Hence, a brief sensitivity analysis was carried out for the full-resistance scenario of a WWL rotation on the weed-free yield of wheat. The model was run with a 23 percent higher weed-free yield for wheat. This means, for example, that the wheat yield following a lupin crop increases from 1.7 to 2.1 t ha^{-1}.

Table 8. Effect of green manuring on annuity under different initial ryegrass seed bank numbers at a higher weed-free wheat yield for a scenario of full resistance to herbicides of Group A and B in a WWL rotation. The net value of green manuring is also represented.

Initial ryegrass seed bank numbers (seeds m^{-2})	Annuity with GM ($/ha/yr)	Annuity with no green manuring ($/ha/yr)	Net value of green manuring ($/ha/yr)
100	120	120	0
200	115	114	1
400	110	108	2
800	104	101	3
1600	98	94	4

A comparison between the results of Table 8 (lower yield) and the results of Table 4 (higher yield) suggests that an increase in wheat yield reduces the relative weed control effectiveness of green manuring, regardless the initial seed bank numbers. However, only a slight increase ($1 ha^{-1} yr^{-1}) in the net value of green manuring in the extreme cases of 100 and 1600 seeds m^{-2} occurs in the scenario with the higher yield.

The role of pasture

In order to investigate the value of green manuring in a situation with better weed control, the model was run for a WWL rotation including a 3-year cadiz serradella pasture phase in years 14 to 16. A full-resistance scenario was assumed.

Table 9. Effect of green manuring (GM) on annuity under different initial ryegrass seed bank numbers for a scenario of full resistance to herbicides of Group A and B in a WWL rotation including a cadiz serradella pasture phase in years 14-16. The net value of green manuring is also represented.

Initial ryegrass seed bank (seeds m^{-2})	Annuity with GM ($/ha/yr)	Annuity with no GM ($/ha/yr)	Net value of GM ($/ha/yr)
100	78	82	-4
200	76	78	-2
400	73	73	0
800	69	67	2
1600	64	62	2

When comparing Table 9 with Table 4 (full-resistance scenario- 0 shots left), the value of green manuring is consistently lower across the different initial seed bank numbers in the rotation with the pasture phase (-$4 to $2 ha^{-1} yr^{-1}) than in the continuous cropping rotations (-$1 to $3 ha^{-1} yr^{-1} for WWL and $0 to 44 ha^{-1} yr^{-1} for WLWC).

This is because pasture provides better weed control than cropping due to grazing and the use of non-selective herbicides. Hence, as more pasture is included in the rotation, the less need for extreme weed control measures.

These results confirm the hypothesis that effective control (with profitable control methods) decreases the value of green manuring as part of an integrated weed management strategy.

CONCLUSIONS

When investigating the value of green manuring in the integrated management of herbicide-resistant annual ryegrass, the main conclusions are that this practice provides very effective control of weed numbers and that it increases value as the number of weeds increases in the system. This may be due to a larger initial seed bank (up to 1600 seeds m-2) or to a higher total germination of the weed (up to 90 percent). The value of green manuring also increases as its control level goes up from 90 to 100 percent or, in some situations, when a higher-performing wheat crop is used in the rotation (but not sacrificed). On the contrary, effective weed control provided by selective herbicides of Group A and B or the inclusion of a pasture phase in the rotation reduces the value of green manuring. In addition, a more diverse cropping rotation (WLWC) allows for more effective management when availability of selective herbicides is particularly restricted.

Another conclusion drawn from this analysis is that an effective complementing control strategy (e.g. glyphosate, tickle and 20 days delaying sowing of lupins) proved profitable in the green manuring phase. More importantly, green manuring becomes a more attractive practice when combined with excellent weed control in the previous year. That way the seed bank is driven to a very low level, requiring an easier and less costly weed management strategy in the following years.

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APPENDIX

Table 1A. Effect of herbicide use, initial ryegrass seed bank numbers and green manuring on annuity and ryegrass seedbank numbers in year two, for two different cropping rotations.

Ability to use Group A&B herb. due to resistance (no. of applic.)	Initial ryegrass seed bank (seeds/m2)	Green manuring	WWL Annuity ($/ha/yr)	WWL Ryegrass seeds/m^2 in year 2	WLWC Annuity ($/ha/yr)	WLWC Ryegrass seeds/m^2 in year 2
0	100	Yes	80	124	63	101
0	100	No	81	124	63	101
0	100	Net value	**-1**		**0**	
0	200	Yes	76	244	59	200
0	200	No	75	244	58	200
0	200	Net value	**1**		**1**	
0	400	Yes	72	477	54	390
0	400	No	70	477	52	390
0	400	Net value	**2**		**2**	
0	800	Yes	67	910	49	745
0	800	No	64	910	45	745
0	800	Net value	**3**		**4**	
0	1600	Yes	61	1669	43	1368
0	1600	No	58	1669	39	1368
0	1600	Net value	**3**		**4**	
2	100	Yes	89	48	76	26
2	100	No	94	48	80	26
2	100	Net value	**-5**		**-4**	
2	200	Yes	88	96	74	51
2	200	No	91	96	77	51
2	200	Net value	**-3**		**-3**	
2	400	Yes	86	191	71	102
2	400	No	87	191	74	102
2	400	Net value	**-1**		**-3**	
2	800	Yes	83	375	68	204
2	800	No	82	375	70	204
2	800	Net value	**1**		**-2**	
2	1600	Yes	78	725	65	403
2	1600	No	76	725	65	403
2	1600	Net value	**2**		**0**	
6	100	Yes	101	58	99	26
6	100	No	108	58	108	26
6	100	Net value	**-7**		**-9**	
6	200	Yes	100	115	99	51
6	200	No	106	115	107	51
6	200	Net value	**-6**		**-8**	
6	400	Yes	99	228	99	102
6	400	No	103	228	106	102
6	400	Net value	**-4**		**-7**	
6	800	Yes	98	448	98	204
6	800	No	99	448	104	204
6	800	Net value	**-1**		**-6**	
6	1600	Yes	95	865	96	403
6	1600	No	94	865	101	403
6	1600	Net value	**1**		**-5**	

Table 2A. Effect of weed control in the first year of the rotation and of green manuring on annuity and ryegrass seed bank numbers in year two.

Weed control in the first year of the rotation	Green manuring	Annuity ($/ha/yr)	Ryegrass seed bank in year 2 (seed/m^2)
40%	Yes	45	10701
	No	46	10701
	Net value	**-1**	
50%	Yes	46	10131
	No	46	10131
	Net value	**0**	
60%	Yes	47	9360
	No	47	9360
	Net value	**0**	
70%	Yes	48	8480
	No	48	8480
	Net value	**0**	
80%	Yes	50	7226
	No	50	7226
	Net value	**0**	
90%	Yes	53	5694
	No	52	5694
	Net value	**1**	
95%	Yes	55	4507
	No	53	4507
	Net value	**2**	
98%	Yes	57	3811
	No	55	3811
	Net value	**2**	
99%	Yes	58	3561
	No	55	3561
	Net value	**3**	
99.9%	Yes	58	3328
	No	56	3328
	Net value	**2**	

Table 3A. Effect of ryegrass seed germination, initial ryegrass seed bank numbers and green manuring on annuity and ryegrass seed bank numbers in year two, for two different cropping rotations.

			WWL		WLWC	
Ryegrass seed germination %	Initial ryegrass seed bank (/m2)	Green manuring	Annuity ($/ha/yr)	Ryegrass seeds/m^2 in year 2	Annuity ($/ha/yr)	Ryegrass seeds/m^2 in year 2
70	100	Yes	83	115	67	95
70	100	No	87	115	69	95
70	100	Net value	**-4**		**-2**	
70	200	Yes	81	227	63	189
70	200	No	82	227	64	189
70	200	Net value	**-1**		**-1**	
70	400	Yes	77	446	58	370
70	400	No	77	446	58	370
70	400	Net value	**0**		**0**	
70	800	Yes	72	858	52	713
70	800	No	70	858	51	713
70	800	Net value	**2**		**1**	
70	1600	Yes	66	1599	46	1334
70	1600	No	64	1599	45	1334
70	1600	Net value	**2**		**1**	
90	100	Yes	77	133	58	93
90	100	No	75	133	57	93
90	100	Net value	**2**		**1**	
90	200	Yes	73	263	54	183
90	200	No	70	263	52	183
90	200	Net value	**3**		**2**	
90	400	Yes	68	511	50	359
90	400	No	64	511	46	359
90	400	Net value	**4**		**4**	
90	800	Yes	63	966	45	688
90	800	No	59	966	40	688
90	800	Net value	**4**		**5**	
90	1600	Yes	58	1747	40	1273
90	1600	No	53	1747	35	1273
90	1600	Net value	**5**		**5**	