Optimal Herbicide Strategies Given Yield and Quality Impacts of Weeds

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Prices received by Australian wheat farmers have increasingly depended on grain quality, especially protein concentration. This concentration depends on various agronomic and physical factors including weed competition. In this paper a model of weed management in the presence of grain quality premiums is presented. Two types of quality premium are examined: a continuout linear payment schedule and a discontinuous "stepped" schedule with substantial premiums for quality levels above a critical level. The model is applied to an analysis of the impact of protein premiums on optimal management strategies for a particular weed in Western Australia. It is found that the impact of protein premiums on optimal weed management is likely to be very small indeed, even if premiums were substantially increased above current levels.

1. Introduction

The quality of wheat grain produced has recently assumed an increased importance to Australian farmers due to the introduction of price incentives for higher protein levels. One of the determinants of protein level in wheat is the extent of competition with weeds for moisture and nitrogen. In addition, there is a range of "dockage" penalties charged against wheat if it is contaminated with impurities (such as weed seeds) above particular levels. Thus the weed competition in a wheat crop affects not just the crop yield (e.g. Pannell 1990a) but also the price received per tonne.

If weeds affect grain quality and grain quality affects price, there is an incentive to modify herbicide use relative to cases where price in independent of quality. However, existing studies of the economics of weed management have focused on yield losses from weed competition (e.g. Auld *et al.*, Pandey and Medd, Pannell, 1990a, 1990b, 1990c, Abadi Ghadim and Pannell). The only published analysis to identify optimal weed management strategies when there are both yield and quality dimensions to the problem is by Marra *et al.*, who calculated weed control thresholds for potatoes in Maine.

Part of the reason for interest in this topic is the recent rapid increase in Australia of cases of herbicide resistance in populations of ryegrass (Schmidt *et al.*). If protein premiums change the frequency of herbicide use, they are likely to change the rate of development of herbicide resistance.

In this paper I extend an existing model of yield competition to include quality reductions and undertake some numerical analyses looking at the impact of price incentives for higher protein levels in wheat. My aims are (a) to understand how the quality issue affects optimal weed control decisions and (b) to determine if and when wheat protein payments have a substantial impact on optimal weed control strategies. I am interested in whether changes in herbicide use have the potential to help arrest the recent decline in protein content in Australian wheat. It may provide an alternative to the usually discussed strategies of increasing nitrogen fertilizer and employing legume rotations.

2. Impacts of Weeds on Wheat Quality

Mason and Madin outline the results of a range of field trials examining the impact of weeds on the protein content of wheat. They conclude that weed competition interacts in a complex way with soil fertility and rainfall to determine the concentration of protein. Their trials included examples where grain protein concentrations were decreased, increased and unchanged as a result of controlling weeds. Decreases in protein concentration may occur where reduced competition for moisture results in a higher grain yield, diluting the concentration of nitrogen in grain. An increase in protein was observed where an excessive nitrogen level in the soil caused "burning off", reducing grain yields and increasing the concentration of nitrogen in grain. For the purposes of this study it is assumed only that the farmer is able to predict the direction and extent of changes in protein level as a result of weed control.

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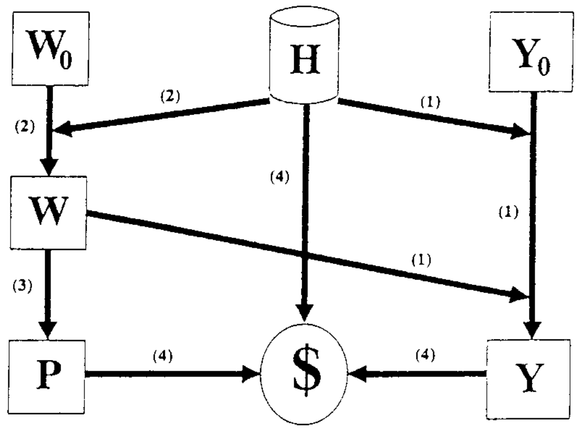
3. The Model

The model used here is an extension of the model presented in Pannell (1990c). Its general structure is illustrated in Figure 1. Numbers in the figure refer to equation numbers in this paper and indicate a correspondence between the equation and one of the linkages in the figure. Symbols used in Figure 1 and in the following equations are explained in Table 1.

Figure 1: Relationships of the Herbicide/ Weed/Crop Model



Crop yield (Y) is represented using the following general form.

(1) $Y = Y_0[1 - D(W)][1 - Z(H)]$

where Y_0 is yield with no weeds present, D is the damage function representing the proportion of yield lost at weed density W and Z is proportional yield loss due to phytotoxic damage by the herbicide. W is a function of W_0, pre-treatment weed density, and K(H), the proportion of weeds killed at herbicide rate H.

(2) $W = W_0\ [1 - K(H)]$

The kill function must be bounded by zero and one and be an increasing function of H. Output price (P_y) is a function of weed density, due to the impact of weeds on grain quality:

(3) $P_y = f(W)$

f will depend on a range of other factors other than weed density, such as crop variety, fertilizer usage and crop yield. Profit (π) is given by

(4) $\pi = P_yY - P_h H - A - F$

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

Table 1: Symbols used in Figure 1 and in the Equations

	Unit	Mean	CV	Description
D	-			Proportional yield loss due to weed competition
H	kg ha^{-1}			Herbicide dosage (in active ingredient terms)
K	-			Proportion of weeds killed at herbicide dose H
W	m^{-2}			Weed density in the crop
W_0	m^{-2}	400	0.21	Pre-treatment weed density in the crop
Y	kg ha^{-1}			Actual crop yield
Y_0	kg ha^{-1}			Weed-free crop yield
Y_1	kg ha^{-1}	1.21	0.40	Weed- and herbicide-free crop yield
π	$A/ha			Profit
P_y	$A/tonne	130	0.20	Crop price for 10 percent protein
P_h	$A/kg	48		Herbicide cost
A	$A/ha	2.5		Fixed application cost for herbicide
F	$A/ha	63		Crop production costs other than herbicide

4. Herbicide Decision Rules

Pannell (1990c), using a similar model but without quality effects, formally derived equations for the optimal herbicide dosage and the threshold weed density (the lowest density at which application of the recommended herbicide dosage is economically justified). The model used here differs by virtue of equation (3). Here the potential impact of (3) on the herbicide decision rules is examined.

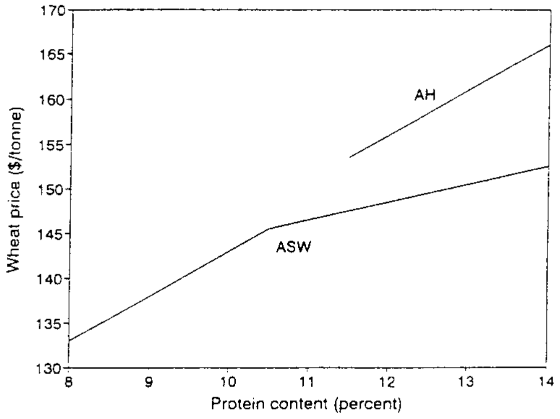
Initially assume that output price increases in a smooth (integrable) manner with every increase in weed density: $dP_y/dW>0$. The smoothness assumption is reasonable for those wheat crops which will definitely be sold as a particular grade of wheat (such as Australian Standard White, ASW) because the increments on which protein premiums are paid are small. For Australian farmers in 1995 the price received for wheat increased for each 0.1 percent increases in protein concentration, with typical protein levels ranging from 8 to 15 percent. Later I will examine a case where the wheat might be sold as either of two grades depending on the protein level.

Increasing herbicide dose decreases weed survival, so $dW/dH<0$. In combination these relationships imply that output price decreases with herbicide dosage: $dP_y/dH<0$. This, then provides an incentive for reduced herbicide use, other things being equal. Conversely in cases where where weeds reduce protein content, there will be an incentive for increased herbicide usage.

Whichever of these two cases occurs (increased or decreased protein concentration due to weeds), there is another means by which protein premiums influence the incentive for herbicide use. They lead to increased use of nitrogen fertilizer which has the effect of increasing crop yields. Pannell (1990c) showed that higher weed-free yields increase the incentive for herbicide use due to the greater value of damage which weeds cause in higher yielding crops. For simplicity I will assume here that these problems are separable. In the numerical results presented below, the weed free yield is assumed to reflect the higher use of nitrogen when protein premiums are paid.

Now consider the case where the wheat is of a variety which might be sold as either of two grades (e.g. ASW or Australian Hard, AH) depending of the protein level. Within each of these grades a premium is paid for extra protein, but there is a substantial bonus payment for the higher grade at all protein levels above a particular minimum level. The 1993/94 schedule of payments for Australian wheats delivered in Perth, Western Australia is illustrated in Figure 2. AH wheat attracts a bonus of at least $12.50/tonne over ASW provided it has a protein level of 11.5 percent or more.

Figure 2: Price Schedules for Australian Standard White & Australian Hard Wheats



Under certainty, the existence of bonus payments for higher grades means that the marginal benefits or costs of herbicide application are potentially very large. At a protein concentration just below that required to allow the crop to be sold at a higher grade, a small change in herbicide use may make the difference between receiving the high-grade bonus and not receiving it. In reality, uncertainty inherent in the decision means that the expected value of benefits of extra herbicide application will be less than it might be in the riskless situation described above (where only a small change in protein level causes a large increase in price). This is because in a deterministic framework, increasing the value of protein can increase the probability of receiving the premium from zero to one, whereas in a stochastic framework, the change in probability is likely to be much less. This is reflected in the numerical examples given later.

The impact of a high-grade bonus on expected sale price can be represented in the following way. For simplicity assume that the payment which increases smoothly with protein level (function f from equation 3) is independent of the grade into which the wheat is sold. Also assume that there exists a critical weed density W_b above which the crop attracts the bonus payment for a higher wheat grade (i.e. assume that weeds increase grain quality). Represent the bonus payment for the higher grade of wheat as g(W), a binary function with value b if $W>W_b$ or zero if $W \leq W_b$.

$$(5)\quad g(W) = \begin{cases} b, & W > W_b \\ 0, & W \leq W_b \end{cases}$$

Uncertainty about W may be due, for example, to uncertainty about initial weed density or herbicide effectiveness. Given that weed density is uncertain, the expected grain price is given by

$$(6)\quad E(P_y) = f(E[W]) + b.\Pr(W>W_b)$$

where E indicated the expected value and Pr indicates probability. We know that $dW/dH<0$ and $dW_b/dH=0$, so as herbicide dose decreases, $\Pr(W>W_b)$ increases, leading to a higher expected price: $dE(P_y)/dH<0$.

The introduction of a bonus provides two different types of incentive to change herbicide usage. Firstly, when the bonus is in place, changing the dose changes profit directly by changing $\Pr(W>W_b)$. If weeds increase grain quality, the potential to change $\Pr(W>W_b)$ provides an incentive to reduce herbicide use, while if weeds decrease grain quality, the incentive is to increase herbicide use. As well as this, the introduction of a bonus payment for high grain quality increases the expected value of grain price, which itself provides an incentive to increase herbicide use because it increases the value of avoiding yield losses (Pannell 1990c). This is true regardless of whether weeds increase or decrease grain quality. In the case where weeds increase grain quality, the two incentives act in opposite directions, whereas if weeds decrease quality, both incentives act to increase herbicide use.

In presenting this model I have used protein as the measure of quality. However the other main quality factor, weed seed contamination, would also fit well in the model. In Australia, where penalties for high weed seed numbers are substantial and lumpy (discrete), the appropriate model for weed seed contamination would include g(W) but f(W) would be a constant rather than a sliding scale. Price would decrease by a discrete amount for weed densities above a critical value.

5. Numerical Model

The problem selected for analysis was control of ryegrass in wheat by application of Hoegrass (active ingredient diclofop-methyl). Farmers in Western Australia consider ryegrass to be one of their most important crop weeds (Roberts *et al.*) and it is the weed with the greatest capacity to develop herbicide resistance. The basic biological relationships were taken from Pannell (1990c).

The yield function (1) is:

$$(7)\quad Y = Y_0\,[1 - \frac{0.544}{1 + 0.544/(bW)}]\,[1 - 0.149H]$$

where

$$(8)\quad b = 0.0172.\exp(-0.801Y_0).\exp(-5.70H)$$

Weed survival (2) is given by:

$$(9)\quad W = W_0/[1 + \exp(F)]$$

where

$$(10)\, F = -2.85 - 0.995\ln(H) - 0.00559\,W_0 - 0.00366\ln(H)W_0$$

Different versions of equations (3) and (6) were tested, representing different protein premiums and grade bonuses. Due to the lack of clear experimental results, the relationship between weed density and protein level was also subject to sensitivity analysis. It was assumed that changes in protein are proportional to yield losses due to weeds.

Templates for a microcomputer spreadsheet program were developed for deriving optimal herbicide rates and thresholds for a single year. Copies of the spreadsheet files are available from the author on request. The numerical analyses were conducted using values for costs, prices, weed densities and yields considered reasonable for the shire of Merredin in Western Australia's eastern wheatbelt (see Table 1).

Stochastic versions of the model were used to assess the impact of bonus payments for high grade wheat. Variability was included in the spreadsheets by entering discrete probability distributions for each uncertain variable or parameter. Coefficients of variation (CVs) for each variable are shown in Table 1. It was assumed that in the absence of weeds, the CV of protein concentration is 0.1. Variation in weed density can further increase the CV of protein level by decreasing protein to a greater or lesser extent. Of course the other impact of weeds is to change the mean protein level so that there is an altered probability that the bonus high-grade payment will be received.

Distributions for output price and initial weed density were generated by a normal random number generator. Implausible values (e.g. negative values of W_0) were eliminated by truncating the distributions. Each randomly generated discrete distribution consisted of 76 observations. This was to maintain consistency with the yield distribution which was generated using a biological simulation model based on 76 years of climatic data. The model is based on CERES Wheat (Ritchie) and has been parameterised and validated for the study region.

The CV of output price was estimated from the residuals of a simple linear regression of recent prices against time to be 0.20. This is similar to the figure of 0.231 reported by Hazell *et al.* for the world market price of wheat during 1941-87. Variance of pre-treatment weed density was estimated from experimental data provided by Hoechst Australia (the manufacturers of Hoegrass).

6. Results and Discussion

All results presented are for the case where weed competition reduces the protein concentration of grain. There is a similar (but converse) set of results for the case where weeds increase protein.

Tables 2 and 3 show results from a deterministic version of the model in which there are price premiums for high protein but no bonus for higher grade wheat. Results are shown for five levels of price premium, ranging from zero to $20 per tonne of wheat per percent of protein. The premium paid in 1993/94 was between $2 and $5/tonne/percent for levels above eight percent (see Figure 2). The tables also show results for different impacts of weeds on protein level. Considering the results of Mason and Madin, a realistic impact is probably not more than a 1 percent reduction at a weed density of 400m^{-2}. Results are also shown for 0.5, 2 and 4 percent reductions. Note that results for zero protein loss are equivalent to results for zero protein premium.

Results in Table 2 indicate that the optimal herbicide dose is affected very little by the protein premiums currently offered to farmers. Even if the premiums increased to $10/tonne/percent, the increase in herbicide dose relative to zero protein premiums is likely to be less than 10 percent. The response to premiums of $20/tonne/percent is more pronounced. Although such premium levels may seem unrealistic given current levels, it is notable that in the US domestic market in late 1993, premiums paid in the market were substantially above $20.

Table 2: Optimal Herbicide Dose (kg a.i./ha): Deterministic Model With No Discrete High-grade Bonus

Protein loss at 400 weeds m^{-2} (%)	Protein premium ($ tonne^{-1} percent^{-1}) 2.5	5.0	10.0	20.0
0.0	0.31	0.31	0.31	0.31
0.5	0.32	0.32	0.33	0.34
1.0	0.32	0.32	0.33	0.35
2.0	0.32	0.33	0.34	0.36
4.0	0.33	0.34	0.36	0.38

The thresholds shown in Table 3 are weed densities above which use of the fixed, recommended herbicide dose (0.375 kg active ingredient per ha) will produce benefits in excess of costs. This is an approach to herbicide decision making which is relevant to those farmers who are not prepared to use herbicide rates other than that shown on the label, or who prefer a simpler decision rule. Results in Table 3 are consistent with Table 2 in that the trend towards higher herbicide dose at higher protein premiums or higher protein losses is reflected in lower threshold densities.

Table 3: Threshold Weed Density (Plants m^{-2}): Deterministic Model With No Discrete High-grade Bonus

Protein loss at 400 weeds m^{-2} (%)	Protein premium ($ tonne^{-1} percent^{-1}) 2.5	5.0	10.0	20.0
0.0	45	45	45	45
0.5	42	39	35	29
1.0	41	38	32	26
2.0	39	35	28	21
4.0	36	30	22	15

Pannell (1990c) found that the weed threshold is more sensitive to changes in parameters than is the optimal herbicide dose, and this trend is evident in Tables 2 and 3. For example, for protein premium of \$10 and protein loss of 2 percent, the optimal dose increases by 10 percent while the threshold density decreases by 38 percent. This greater sensitivity of the numerical value of the threshold does not necessarily mean that the farmer's behaviour is more likely to change. Whether the change in threshold would result in a change in herbicide usage depends on the actual weed density. If, for example, the actual weed density is substantially above the threshold, reductions in the threshold will have no impact on behaviour. Densities of ryegrass well above those of Table 3 are certainly common on Australian wheat farms.

Tables 4 and 5 show the impact on optimal rates and thresholds of bonus payments for high grade wheat. These results are based on a comparison of results for bonuses of zero and \$15 per tonne. Results are based on a normal probability distribution for weeds with a mean of 400 and a CV of 0.21. Results are shown for three values of expected protein content in the absence of weeds: 9.5, 11.5 and 13.5 percent. This is to investigate the importance of the position of the probability distribution of protein relative to the critical value required to achieve bonus payments (11.5 percent). For each of these expected protein levels, the actual protein level depends on a random draw from the distibution for weed-free protein level, on the initial weed density (which is also a random variable) and on the level of weed control. Results are also shown for different impacts of weeds on protein, ranging up to the improbably high value of 4 percent for 400 weeds m^{-2}.

Table 4: Increase in Optimal Herbicide Dose Caused by Introduction of Bonus (\$15 tonne^{-1}) for High Grade Wheat

Protein loss at 400 weeds m^{-2} (%)	Expected Protein Content (%) 9.5	11.5	13.5
0.0	0.00	0.00	0.01
0.5	0.00	0.00	0.01
1.0	0.00	0.00	0.00
2.0	0.00	0.00	0.00
4.0	0.00	0.00	0.00

Table 5: Decrease in Threshold Weed Density Caused by Introduction of Bonus (\$15 tonne^{-1}) for High Grade Wheat

Protein loss at 400 weeds m^{-2} (%)	Expected Protein Content (%) 9.5	11.5	13.5
0.0	0	2	4
0.5	1	3	4
1.0	0	3	4
2.0	1	7	5
4.0	1	8	7

In all scenarios (including others not shown here), the impact of the bonus payments on optimal herbicide decision rules is very small and only slightly greater for the value of the threshold. This highlights the importance of using a stochastic model to evaluate this issue. In a deterministic model, the addition of extra protein would make a large impact on profit in some scenarios, but in a stochastic model it can only shift the probability distribution of protein. The benefit is then only the increase in expected value of the bonus payment resulting from the extra herbicide. This benefit is never sufficient to warrant a substantial change in herbicide strategy in the model presented here. When one considers that the impact on profit of the indicated management changes are proportionally even smaller, the overall significance of this issue is very small indeed.

7. Concluding Comments

Overall, results indicate that the impact of payments for protein level and bonus payments related to minimum protein levels are likely to have a low impact on herbicide use in Australia, even if the value of payments were to be increased substantially. The numerical results presented are only for a single weed, but they are so clear-cut for this relatively competitive weed that it seems unlikely that substantial effects would occur for other weeds. Results for the case where weeds increase grain quality are not presented here, but they are similarly insensitive. If the introduction of premiums for protein content is to have a substantial impact on the protein content of Australian wheats, it will have to be via a mechanism other than changes in herbicide use.

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