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WEED MANAGEMENT IN CROP-PASTURE ROTATIONS

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WEED MANAGEMENT IN CROP-PASTURE ROTATIONS

Abstract

On wheat-sheep farms in the south-west of Western Australia, pasture production in winter is a major limiting factor for the sheep enterprise. This paper describes an economic evaluation of reducing herbicide usage in crops below recommended levels to increase subsequent pasture production in pasture-crop rotations. The analysis was conducted using MIDAS, a whole-farm linear programming model. Inputs to MIDAS were provided by a simulation model of the weed population and regression models of weed kill from herbicide application and yield response to weed removal. The analysis was of ryegrass (Lolium rigidum) control by Hoegrass in the Merredin region. Results indicated that the gains from increased sheep and wool production and reduced herbicide cost are likely to exceed the losses from reduced grain yield. This conclusion is found to be insensitive to major biological and economic assumptions of the analysis.

Introduction

Pasture production during winter is one of the main factors limiting production and profitability of the sheep enterprise in the wheat-sheep farming system of Western Australia's wheatbelt. In the weeks following pasture germination, feed availability is at its lowest level for the year, so it is this period which determines overall carrying capacity. The problem is worst in crop-pasture rotations since the pasture seed bank is reduced by weed control practices in the crop phase.

Ewing and Pannell (1987) found that in the eastern wheatbelt the value of extra pasture in May-July is substantially greater than the value of an equivalent increase in spring, when production is at its peak. A number of strategies for overcoming the winter "feed gap" have been suggested, including undersowing legume pasture species in the crop, grazing livestock on tagasaste (Chamaecytisus palmensis) (Oldham and Moore 1989), supplementary feeding of grain or treated crop residues (Rowe 1986; Aitchison 1988), increasing pasture density through research to increase seed production (Williams and Allden 1976) and breeding pastures with high early growth rates. Of the strategies involving pasture, those operating through increased pasture density appear promising (Donald 1951) while attempts to increase early growth rates do not (Collins et al. 1983).

In this study, we examined a potential strategy which has so far received very little attention: reductions in the level of weed control in the crop phase of pasture-crop rotations. As well as increased pasture production, this strategy has the additional benefit of reduced weed control costs. However these benefits are only achieved at the expense of a reduction in crop yield. The question addressed here is whether, in a particular circumstance, the benefits of reducing rates of herbicide use are likely to exceed the costs. We considered the case of a ryegrass (Lolium rigidum) pasture growing on gravelly sand/sandy gravel soil types in the Merredin region. We assumed that ryegrass was controlled in the crop phase by application of Hoegrass after weed emergence. A range of six pasture-crop rotations were considered, from three years of pasture followed by one crop through to one pasture-three crops.

Materials and Methods

The analysis was conducted using MIDAS, a whole-farm linear programming (LP) model (Kingwell and Pannell 1987). Regression models of weed kill from herbicide application and yield response to weed removal and a simulation model of weed population dynamics provided inputs to the LP model. These models are further described below.

The linear programming model

The following model description is based on Pannell and Falconer (1988).

MIDAS is the product of interdisciplinary co-operation at the Western Australian Department of Agriculture, South Perth, and the Western Australian Dryland Research Institute, Merredin. The model building procedure was described by Morrison et al. (1986). In summary it consisted of four stages: (1) discussions with a wide range of experts 'to identify, usually through consensus, a set of decision variables, inter-relationships and constraints which properly described the whole-farm system' (Morrison et al. 1986, p.245); (2) model construction and documentation; (3) quantification of model coefficients with data from publications, field trials, surveys, market reports and discussions; and (4) model revision and validation. This procedure is part of an ongoing process and the model has continued to evolve and improve. In this study we used version EWM 65 which is updated to 1988.

The version of MIDAS used here includes approximately 400 activities and 200 constraints with the objective of profit maximization. It selects the most profitable combination and level of farm activities subject to the constraints of the farm system. The activities are the alternative crop, pasture and livestock options and all associated activities, such as machinery purchase and use, shearing, fertilizing, hiring labour and borrowing finance. The constraints include: limits on resources such as land, labour and capital; biological constraints such as the relationship between fertilizer rates and yield; and technical constraints such as those which relate machinery size to potential seeding rates. Model coefficients are too numerous to be presented here. The reader is referred to Kingwell (1987) and Morrison et al. (1986) for details of the model's structure and contents.

MIDAS is a single-year equilibrium model which identifies a long-term optimal strategy using 'average' season parameters but does not determine how a particular farmer might move from his or her current position to that optimum. It is based on a typical farm as described below but can easily be adapted to represent any specific farm in the region.

The farm system modelled by this version of MIDAS is based on Merredin in Western Australia's eastern wheatbelt, where annual rainfall averages 310 mm with average growing season (May to October) rainfall of 250 mm. Cereal crops in the region (and the model) are wheat, barley, oats and triticale and there are two legume crops: lupins and field peas. Pastures normally contain little legume except on some soils with a higher clay fraction. Soils are highly weathered and infertile; wheat yields in the Merredin shire average 1.0 tonnes per hectare. Six broad soil type categories representative of Merredin are included in the model in proportions typical for the region (see Table 1). Farm area used in the study is the shire average of 2300ha. Crops and pastures are commonly grown in rotation, with a recent trend towards cereal-lupin rotations. Most farms are owner operated with not more than one other permanent labourer.

Table 1: Soil types represented in whole-farm model

Soil description	pH	Area (per cent)
1 Loamy/gravelly sands	< 5.5	20
2 Deep loamy sands	5.5-6.0	20
3 Gravelly sands/sandy gravels	5.5-6.0	10
4 Loamy sand over clay	5.5-6.5	10
5 Sandy loam over clay	6.0-7.0	15
6 Sandy clay loam	> 6.5	25

One of MIDAS's particular strengths, and the main reason for using it in this analysis, is its ability to calculate the economic value of pasture. Estimating pasture value is very difficult, especially in a mixed farming system. Pannell and Panetta (1986) identified a number of complexities which need to be considered. These complexities are described here to illustrate how difficult it would be to conduct this analysis without use of a whole-farm model such as MIDAS.

1. The marginal value of a unit of pasture depends on which factor is limiting production. If pasture is limiting, its value is high but if another factor, such as labour, is limiting and pasture is in excess supply, the marginal value of pasture is zero.

2. The availability of other sources of fodder sets an upper limit on the value of pasture.

3. The value of pasture varies within the season due to variations in pasture production, feed requirements of animals and prices of animals and alternative feeds.

4. Grazing of pasture may be delayed but at some cost due to deterioration and the opportunity cost of the pasture not grazed in the earlier period.

5. The opportunity cost of competing farm enterprises must be considered. For example, there is little value in increased pasture production on a soil for which cropping is more profitable.

6. The values of pasture and crop are interdependent due to nitrogen fixation by legume components of pasture, disease break effects, reductions in pasture density after cropping, increases in weed density in crop after pasture and the contribution which crop residues make to livestock diets.

MIDAS includes each of these complexities in calculating the value of pasture.

Increases in pasture density have greatest impact on pasture production early in the growing season. While seedlings are small, inter-plant competition is minimal so that pasture production is approximately a linear function of density. The larger the plants grow, the greater is the effect of competition and the lower is the influence of density on production. For the purposes of this evaluation, we assume conservatively that improvement in pasture production occur only in the first three months of the growing season: May to July.

In rotations including more than one consecutive crop, it is conceivable that herbicide rates could be reduced in each year of crop. However in this study we evaluated only the strategy of reducing rates in the crop immediately preceeding pasture.

Weed survival regression model

Data from field trials of ryegrass control by Hoegrass were obtained from Hoechst Australia Ltd, the manufacturers of Hoegrass. Unfortunately not all relevant variables had been recorded for each trial. In particular, the weed density prior to herbicide application was frequently not recorded. Since this variable constitutes the information about weed density available to farmers at the time when spraying decisions are made, it was considered crucial for this study. There were four trials in which all desired variables were measured. These were conducted in New South Wales and Victoria in 1975 and 1976. There were 96 observations in the data set.

The general form of the weed survival function is

$$W = W_0 \, [1 - K(H)] \tag{1}$$

where

W is surviving weed density (m^{-2}),

W_0 is pre-treatment weed density (m^{-2}),

H is herbicide rate (kg active ingredient ha^{-1}) and

$K(H)$ is a logistic kill function (Ashton 1972) giving the proportion of weeds expected to survive application of herbicide rate H:

$$K(H) = 1/[1 + \exp(-\alpha - \beta H)] \tag{2}$$

Substituting (2) into (1), slightly rearranging and adding an error term (ϵ) gives the following function used for estimation purposes:

$$W/W_0 = \{1/[1 + \exp(\alpha + \beta H)]\} + \epsilon \tag{3}$$

The standard assumption in probit or logit analysis is that the error term is binomially distributed (e.g. Finney 1971). However the assumption was not appropriate for this data set which displays variance increasing monotonically with weed survival. The reason for the difference is that in standard logit analysis, the number of organisms treated is known (or assumed to be known) exactly, whereas in this study the pre-treatment density had to be estimated by sampling. Wadley (1949) described a problem of this type involving heat treatment of bacterial spore suspensions. In that study the number of organisms treated (n) was estimated from parallel untreated samples. Wadley argued that the estimate of the number of organisms surviving treatment will have two sources of variance: the usual binomial variance "which would be present even if n were known exactly" and "the additional variance caused by uncertainty about the value of n" (Wadley 1949, p.197). According to Wadley the variance of n may be usefully approximated by the Poisson distribution in which $Var(n) = E(n)$. A Poisson distribution was found to fit the data well and so was used for the estimation of parameters.

A problem occurred with observations in which 100 per cent weed kill was achieved, resulting in zero survival. The estimation algorithm involved taking logs of post-treatment density, so it was assumed that in all cases at least one weed per square metre survived treatment.

The function to be estimated is consistent with the definition of a Generalised Linear Model (GLM) (Nelder and Wedderburn 1972) so the microcomputer version of GLIM was used for the estimation. Estimated parameters for the model are shown below with standard errors in brackets.

$$W/W_0 = \{1/[1 + \exp(1.562 - 12.17.H + 7.710.H^2 - 0.004762.H.W_0)]\}$$
$$\qquad\qquad (0.2769) \quad (1.489) \quad (1.345) \quad (0.001846)$$

Each parameter estimate is significantly different from zero at $p = 0.05$ and the value of r^2 (calculated as $1 - \Sigma(\phi - \hat{\phi})/\Sigma[\phi - E(\phi)]^2$ where $\phi = W/W_0$) is high at 0.86. The sign of the parameter on H is negative, as expected, implying that higher herbicide rates result in lower weed survival. The parameter on $H.W_0$ is also negative indicating that the proportion of weeds killed at a particular herbicide rate is greater for higher pre-treatment weed densities.

<u>Crop yield regression model</u>

Data used to estimate the crop yield function were obtained from the set of trials described above. The data set included 339 observations from 14 trials in Western Australia, New South Wales and Victoria from 1975 to 1981.

The crop yield function has the following general form

$$Y = Y_0 \; [1 - D(W)] \tag{5}$$

where

Y is crop yield (t ha^{-1}), Y_0 is weed-free yield (t ha^{-1}),

W is weed density (m^{-2}) [given by (4)] and
D(W) is a hyperbolic damage function giving proportional yield loss at weed density W (Cousens 1985)

$$D(W) = bW/(1 + bW/a) \tag{6}$$

This is the form which gave best fit in Cousens' comparison of various functional forms. It also has the advantage of readily interpretable parameters; a is the maximum yield loss at high weed densities and b is the marginal yield loss as weed density tends to zero.

Proportional yield loss resulting from a particular weed density is likely to be influenced by a number of factors. For example the proportional yield loss may not be independent of the absolute crop yield. Secondly it is very likely that the competitive abilities of weeds will be inversely related to the amount of herbicide applied to them. It has been observed that herbicides can improve yields by suppressing weed growth even if the weeds are not killed (M.L. Poole, personal communication). These possibilities were allowed for by estimating b as a function of the weed-free crop yield and herbicide rate.

$$b = b_1 \cdot \exp(b_2 \cdot Y_0) \cdot \exp(b_3 \cdot H) \tag{7}$$

This functional form was chosen to reflect the fact that as Y_0 and H reach high levels, b may approach zero but cannot become negative. Substituting (7) into (6) and (6) into (5) and adding a random disturbance term gives the following function used for estimation purposes.

$$Y = Y_0\left[1 - a/\left(1 + a/[b_1 \cdot \exp(b_2 \cdot Y_0) \cdot \exp(b_3 \cdot H)W]\right)\right] \tag{8}$$

The function is highly non-linear and, moreover, is not consistent with the definition of a General Linear Model, so it must be estimated by a general non-linear regression algorithm. The package used in this study was Shazam (White 1978).

Parameter estimates for this model are shown in Table 2. All parameter estimates pass a t test for significant difference from zero at $p = 0.05$ and r^2 (calculated as $1 - \Sigma(Y - \hat{Y})^2/\Sigma[Y - E(Y)]^2$ is 0.90 indicating very good fit by the model. Parameters for b_2 and b_3 are negative, indicating that marginal yield loss declines with increases in Y_0 or H.

Table 2: Parameter estimates for yield model

Parameter	Parameter estimate	Standard error
a	0.5436	0.07114
b_1	0.01722	0.008487
b_2	-0.8010	0.1934
b_3	-5.705	2.0308

The Population Dynamics Model

Population dynamics affect the problem in two ways. Firstly, a reduction in weed control increases pasture densities in subsequent years and, secondly, it affects the weed density which will be encountered in subsequent cropping phases. Unfortunately, published information on the population dynamics of ryegrass in Western Australia is minimal. Changes in ryegrass density were estimated here using a simulation model based on one developed by Cousens et al. (1986). Because of the lack of experimental data, parameters of the model had to be estimated subjectively with guidance from biological researchers. For this reason, the model's predictions of pasture density were not used directly in the analysis. Rather the problem addresses was to determine the increase in pasture production necessary to at least compensate for lost crop yield. It is then up to biological researchers to determine whether these break-even pasture increases are likely to be exceeded in practice. Furthermore, although we did use the population model to predict stable weed densities in subsequent cropping phases, the economic analysis was repeated a number of times to determine whether inaccuracies in our predictions of yield loss would substantially change the result of the analysis.

The first component of the population model is the relationship between seedling density and mature ryegrass plants. This was assumed to be a hyperbolic function:

$$M_t = I_t(1 + \alpha . I_t) \tag{9}$$

where

M = mature ryegrass density
I = ryegrass seedling density
α = a mortality coefficient and
t = time (year).

The magnitude of α was changed according to the phase of the rotation. In the crop phase it was set at 0.0025 while in the pasture phase it was 0.001. Cultivation and inter-species competition result in higher mortality in the crop phase.

Ryegrass seeds exhibit very little dormancy (Gramshaw 1974). In this study a simplifying assumption of zero seed dormancy eliminated the need to consider seedling density as a function of new and old seeds. Seedling numbers were assumed to be a linear function of seed numbers in the soil with the proportion of seeds successfully germinating and surviving to the stage of inter-plant competition given by a recruitment coefficient, G. Values assumed for G were 0.05 in the crop phase and 0.1 in the pasture phase.

Mature ryegrass plants [those resulting from equation (1) and surviving any herbicide application] were assumed to produce an average of 75 seeds (Gramshaw 1974). Thus seed numbers in any year equalled 75 times the number of mature plants the previous year.

Procedure

The analysis was conducted in a long-run equilibrium framework. We compared profits derived from use of recommended herbicide rates with profits achievable under lower herbicide rates after the farm plan had been adjusted to make best use of the increase in pasture availability. Such adjustments may have included increases in stocking rate, changes in flock structure and even changes in the rotation practised.

First, MIDAS was solved for the recommended Hoegrass rate of one litre per hectare of crop on soil type 3. Then model parameters were adjusted to represent the effect of a lower herbicide rate on crop yield and herbicide costs. The model was solved for a number of values of winter (i.e. May to July) pasture production. Results obtained were used to determine how much extra production was required to make the reduced rate as profitable as the recommended rate. This process was repeated for three different Hoegrass rates: 0.75, 0.67 and 0.50 litres per hectare.

Because the analysis was subject to uncertainty about many of the assumptions made, we investigated the sensitivity of results to changes in a number of key parameters. These were the price of wool, the price of wheat, the cost of herbicide and the level of yield lost following herbicide reductions.

Results and Discussion

Results for recommended herbicide rates

A brief summary of the optimal farm plan using recommended herbicide rates is shown in Table 3. Whole-farm profit was calculated as $82500 per year. The optimal crop-pasture rotation on soil type 3 was three years of pasture followed by one year of crop.

Results for reduced herbicide rates

The main results of the study are shown in Figure 1. If the rate of Hoegrass is cut by 25 per cent, an increase of at least 7.7 per cent in May-July pasture production in the following year is needed to compensate for the lost wheat yield. If production increased by more than 7.7 per cent, whole-farm profit would be improved relative to the optimal strategy involving recommended Hoegrass rates. The break-even pasture increases for 33 and 50 per cent rate cuts are 21 and 48 per cent respectively. The lower the herbicide rate used, the greater the yield loss in the crop, resulting in a higher pasture production increase required to break even.

In all model results, the optimal rotation on soil type 3 was 3 pastures-1 wheat.

Table 3: Summary of optimal farm plan

Net annual profit	\$82500
Total sheep numbers	3833
Total weed control costs	\$13000
Land in crop	48 per cent
Rotations†	
Soil 1	PPPP
Soil 2	WL and WWL
Soil 3	PPPW
Soil 4	WWL
Soil 5	WWF
Soil 6	PPPP

† P = pasture, W = wheat, L = lupins, F = field peas.

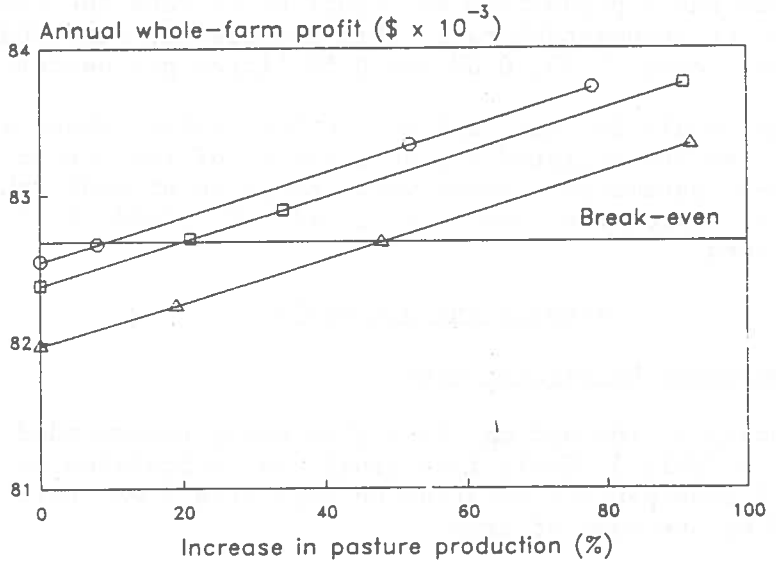

Figure 1: Percentage increase in pasture productivity required to break even at reduced Hoegrass rates. Rates are 0.75 L ha^{-1} (o), 0.67 L ha^{-1} (□) and 0.5 L ha^{-1} (Δ).

Unfortunately, field experiments which would indicate whether these required increases in pasture production are likely to occur have not been conducted. In the absence of empirical evidence, the best available information is the results of the ryegrass population model described above. Early in the growing season, pasture production is closely correlated with density. The increases in density predicted by the population model provide an upper-bound estimate of the production increases which could be expected. Table 4 shows predicted increases in stable ryegrass density for each of the three herbicide rate reductions. In each case the predicted increase in density is many times greater than the required production increase. Even if the actual production increase is proportionally less than the density increase (due to competition between ryegrass plants or with wheat plants), it still seems very likely to be greater than the increase required to break-even. Thus it appears likely that in the circumstances examined here, reductions in Hoegrass rates below recommended rates are likely to improve whole-farm profits.

Table 4: Predicted percentage increases in ryegrass density on soil type 3 in first pasture of a PPPC rotation

Increase is relative to the density following 1.0 L ha^{-1} Hoegrass

Herbicide rate (L ha^{-1})	0.75	0.67	0.50
Ryegrass density increase (per cent)	203	238	400

Sensitivity analysis

Although results reported above are favourable for herbicide reductions, there is uncertainty about parameter values in each of the models. In this section we examine the sensitivity of results to changes in key parameters. The values for which sensitivity analysis was conducted are: the level of yield loss following herbicide reductions, the wool price, the wheat price and chemical costs.

Table 5: Break-even pasture responses (per cent) following herbicide reductions for different levels of yield loss

Proportion of expected yield lost (per cent)	Hoegrass rate (L ha^{-1})	
	0.50	0.67
50	0	0
100	48	21
150	10	42

Yield loss. Table 5 shows pasture responses required to break even for two herbicide rates (0.50 and 0.67 L ha^{-1}) if the yield losses resulting from reduced herbicide rates were 50 per cent above or below the expected levels. If we have overestimated yield loss in our initial analysis, the required increase in winter pasture production is, of course, less than originally calculated. If the extent of overestimation was as great as 50 per cent, the benefits of reduced herbicide rates would exceed the costs even if no extra pasture was obtained. On the other hand, if the yield losses were 50 per cent greater than we have predicted, required pasture increases would be increased by approximately 100 per cent. However, even these levels of pasture production seem achievable in the light of the projected increases in pasture density discussed above.

Wool price. There has been considerable variation in wool prices in recent years. The wool price is important to this analysis as it is a major determinant of the value of extra pasture. When wool price is high, so too is the value of extra pasture, reducing the amount of extra pasture needed to compensate for lost crop yield. Table 6 shows the effect of wool price on the winter pasture increase required to break even. At prices above our original assumption of \$6.50 kg^{-1} (greasy and net of selling expenses) the break-even winter pasture increase declined as expected. However there was an interesting result at \$4.50 kg^{-1}; the required increase in winter pasture declined dramatically. This was not as inconsistent as it may appear. It occurred because at this low wool price the profitability of sheep production had declined sufficiently to cause a change in the optimal rotation from PPPC to CCCP. The effect of a reduction in Hoegrass rate on crop yield is much less in the last crop of a CCCP rotation. This is due to the lower weed density resulting from multiple years of cropping. Although the required pasture increase would be less, the actual pasture increase would also be less due to the lower plant density. However results of the population dynamics model indicate that the required increase could still be achievable. Overall it seems that inaccuracy in our assumed wool price does not affect the result of this analysis.

Table 6: Break-even pasture responses (per cent) following herbicide reductions for different wool prices

Net wool price ($ kg greasy)	Hoegrass rate (L ha^{-1}) 0.50	0.67
4.50	5	8
5.50	48	21
6.50	48	21
7.50	40	14
8.50	27	11

Wheat price. Wheat price may also influence results by affecting the value of grain yield lost after herbicide rate reductions. The wheat price used in the initial analysis was \$144 (net of all selling and transport expenses). However, as shown in Table 7, changes in wheat price do not invalidate our analysis. At lower wheat prices the value of yield lost is lower, so less pasture was required to compensate. At higher wheat prices there was again a change in the optimal rotation to CCCP resulting in lower weed densities, a smaller loss of crop yield and thus a smaller increase in pasture growth required to break even.

Table 7: Break-even pasture responses (per cent) following herbicide reductions for different wheat prices

Net wheat price ($\$ t^{-1}$)	Hoegrass rate ($L ha^{-1}$) 0.50	0.67
110	27	13
144	48	21
170	20	8

Chemical cost. When the patent expires on diclofop-methyl (the active ingredient of Hoegrass), it is very likely that the price of the chemical will fall dramatically. This would reduce one of the benefits of cutting herbicide rates, increasing the break-even winter pasture increase. However even if the price falls as low as $\$7\ L^{-1}$ (from the current level of $\$18\ L^{-1}$) the required pasture increase would not reach infeasible levels (Table 8).

Table : Break-even pasture responses (per cent) following herbicide reductions for different herbicide costs

Hoegrass price ($\$ t^{-1}$)	Hoegrass rate ($L ha^{-1}$) 0.50	0.67
18.00	48	21
7.00	70	39

Conclusion

Reductions in Hoegrass application rates appear likely to increase pasture production sufficiently to increase profit overall for wheat crops grown in rotation with ryegrass pastures on gravelly sands/sandy gravels in the eastern wheatbelt of Western Australia. Because of uncertainty about increases in pasture which will actually occur, we have not attempted to determine optimal herbicide rates for crop-pasture rotations. However we have determined increases in winter pasture production required to break-even. These can now be used as the basis for further field experiments. If trials indicate that actual pasture increases are greater than our calculated break-even levels, reductions in Hoegrass rates can be advocated with more confidence.

Results reported here are conservative (in the sense of overestimating break-even pasture increase) since we have assumed that lower herbicide rates do not increase pasture production after July. Wide ranging sensitivity analysis showed that even if our assumptions are quite inaccurate, increases in winter pasture required to break even are likely to be achievable.

This analysis clearly has implications for other weeds and other herbicides. In general, the optimal herbicide rate to be applied to a pasture species growing in a crop will be lower if the crop is to be followed by a pasture. This does appear to be a strategy deserving further attention.

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