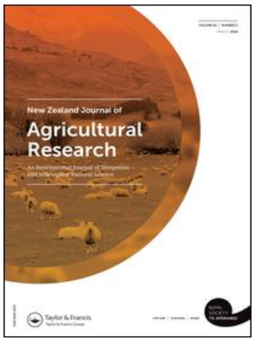

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RESEARCH ARTICLE

Net economic benefit of *Ranunculus acris* control in dairy pasture – accounting for herbicide damage to clovers and evolved resistance

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ABSTRACT
The phenoxy carboxylic acid, ALS-inhibitor and pyridine carboxylic acid herbicides vary in the magnitude and duration of *Ranunculus acris* control in dairy pastures and in collateral damage to clovers. For estimating the net economic benefit from a proposed herbicide treatment, we developed a model accounting for these sources of variation. Applied to a hypothetical dairy pasture with 12 tonnes dry matter/ha/year eaten and assuming present-day costs and prices (e.g. herbicides, nitrogen fertiliser, milksolids pay-out), the model illustrates the expected increase in net benefit with increasing pre-treatment *R. acris* cover. It also predicts lower breakeven covers (C_{BE}) for the phenoxys (MCPA $C_{BE} = 3.72\%$; MCPB $C_{BE} = -0.88\%$; MCPB + bentazone $C_{BE} = 1.51\%$) and ALS-inhibitors (flumetsulam $C_{BE} = 1.88\%$; thifensulfuron methyl $C_{BE} = 1.50\%$) than for the pyridines (aminopyralid $C_{BE} = 7.24\%$; aminopyralid + triclopyr $C_{BE} = 5.72\%$), a result of their lower costs and lower and less-enduring clover damage compared to the pyridines. A greater uncertainty in the net benefit from the phenoxys and ALS-inhibitors results from a greater paddock-scale variation in their efficacy, a characteristic attributable to evolved resistance. The model is available as a weed control decision-support tool at https://giant-buttercup-ds-tool.azurewebsites.net/.

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Giant buttercup; herbicide resistance; meadow buttercup; nitrogen fertiliser; tall buttercup

Introduction

The phenoxy carboxylic acid herbicides MCPA and MCPB, the ALS-inhibitors flumetsulam and thifensulfuron methyl, and the pyridine carboxylic acids aminopyralid and triclopyr are the three dominant 'mode-of-action' classes of herbicides available for controlling giant buttercup (*Ranunculus acris* L.) in pastures (Novachem 2020). They comprise the active herbicide ingredients (either alone or in combination) in 49 herbicide products registered for giant buttercup control in New Zealand (Novachem 2020). These herbicides vary substantially, within and between pastures, in the magnitude and duration of the weed control that they provide (Bourdôt et al. 2019). They also vary in their collateral damage to beneficial nitrogen-fixing clovers (Lusk et al. 2011). Their

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variable weed control efficacy is in part due to evolved resistance of *R. acris* populations to the phenoxy carboxylic acids and ALS-inhibitors (Bourdôt et al. 1990a, 1990b; Bourdôt and Hurrell 1991; Bourdôt et al. 1996; Bourdôt et al. 2007; Lamoureaux and Bourdôt 2007; Lusk et al. 2011; Lusk et al. 2015; Jackman et al. 2020). This complex 'landscape' of herbicide products, herbicide active ingredients, mode-of-action classes, differences in efficacy, evolved resistance, and differences in clover damage, makes it extremely difficult for farmers to select the herbicide most likely to provide profitable control of a specific *R. acris* population in a dairy pasture.

The objective of the work reported here was to develop a model for analysing the economic benefit of different herbicide treatments available for controlling the weed. The model is based on published data for the reduction in the cover of *R. acris* in grazed dairy pastures (Bourdôt et al. 2019) plus newly analysed data on the reduction in the clover content of pastures caused by the different herbicides. We anticipate that the model, implemented as a web-based decision-support tool (Bourdôt et al. 2020), will enable dairy farmers and consultants to determine whether an economic benefit from controlling a given level of *R. acris* infestation in a paddock is likely, and to select the most cost-effective herbicide. Better-informed decisions on the frequency, amount and type of herbicide should help minimise total chemical use and control herbicide resistance evolution in the infested pasture.

Materials and methods

Effects of herbicides on clover content of dairy pastures

To enable the loss in clover due to herbicide damage in dairy pastures to be accounted for in our model for the net economic benefit of controlling *R. acris* (described below), we first require data on these losses. To that end, we analysed the data on the effects of aminopyralid, aminopyralid + triclopyr, flumetsulam, thifensulfuron methyl, MCPA, MCPB and MCPB + bentazone on the clover content (percentage ground cover) in the presence and absence of pre-graze mowing obtained from the 18 pastures in our previous experiment (Bourdôt et al. 2019). We present the results here in this section. We included the pre-graze mowing effect for completeness although the net economic benefit model is for herbicide treatment only, without mowing as an additional *R. acris* control measure. A linear model was fitted to the natural log-transformed percentage cover of the clovers, with the farm and paddock (blocks) combined as a random effect, as was done previously for the combined grass + clover dry matter (Bourdôt et al. 2019). Residuals from the analysis were inspected for violations of the assumptions of the model; log transformation resolved the problems that were identified. Significance of effects was found by comparing models with and without the effect with the appropriate Chi-square statistic. All models were fitted using the lme4 package (Bates et al. 2015) in R (R Core Team 2017).

The results, as back-transformed means of % cover (Table 1) and then as proportional losses (compared to the not-treated control) (Table 2), are inputs for the model that we develop and analyse in this paper. There is strong evidence for a higher cover of clover with the pre-graze mowing treatment compared to the no-mowing treatment when assessed at 7, 19 and 31 months after treatment ($P < 0.0001$) (Table 1). This effect may be in part due to release from competition from the *R. acris* which was significantly

Table 1. The effect of herbicide treatments in the presence (+) and absence (−) of pre-graze mowing on the % ground cover of clovers (mainly *Trifolium repens*) averaged over the 'wet' and 'dry' paddocks and the growth promoter treatments 'gibberellic acid' and 'N fertiliser' as assessed 2, 7, 19 and 31 months after application in our field experiment (Bourdôt et al. 2019). The statistical analysis was conducted on the natural log-transformed values; the means presented in this table are the back-transformed values.

Treatments		Clovers (% ground cover)			
Herbicide	Mowing	2 months [a]	7 months [a]	19 months [b]	31 months [c]
Nil (control)	-	13.5	10.1	11.3	8.3
Aminopyralid	-	0.0	0.1	5.0	8.2
Aminopyralid + triclopyr	-	0.0	0.1	5.3	10.1
Flumetsulam	-	19.1	11.1	12.0	7.4
Thifensulfuron methyl	−	10.8	10.1	12.0	8.1
MCPA	−	5.8	8.1	10.3	7.8
MCPB	−	13.9	11.5	12.5	8.7
MCPB + bentazone	−	16.1	11.7	12.1	7.9
Nil (control)	+	13.9	12.4	15.3	9.1
Aminopyralid	+	0.0	0.1	9.1	12.9
Aminopyralid + triclopyr	+	0.0	0.1	7.9	13.3
Flumetsulam	+	16.9	13.5	15.1	11.4
Thifensulfuron methyl	+	10.4	11.2	16.4	11.8
MCPA	+	4.8	8.7	19.0	10.3
MCPB	+	15.3	13.1	15.5	11.1
MCPB + bentazone	+	13.8	13.8	17.3	8.0
P-values for tests of factorial main effects and interaction contrasts					
Herbicide		<0.0001	<0.0001	<0.0001	<0.0001
Mowing pregraze		0.081	<0.0001	<0.0001	<0.0001
H x **M**		0.0003	0.74	<0.0001	0.014

[a]Averages over nine farms (Year-1, Year-2 and Year-3 farms).
[b]Averages over six farms (Year-1 and Year-2 farms).
[c]Averages over three farms (Year-1).

Table 2. The effect of herbicide treatments in the absence of pre-graze mowing on the proportional reduction in % ground cover of clovers (as compared to the not-treated control) averaged over the 'wet' and 'dry' paddocks and the growth promoter treatments 'gibberellic acid' and 'N fertiliser' as assessed in May each year (7, 19 and 31 months after application [Year 1, 2 and 3 respectively]) in our field experiment (Bourdôt et al. 2019). For the bottom three herbicide combinations which were not included in the field experiment, the means and upper and lower quartiles were set equal to those of the most damaging of the herbicides tested alone.

Herbicide	Mean			Upper quartile			Lower quartile		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Aminopyralid	0.994	0.555	0.015	0.985	0.434	−0.734	1.000	0.922	0.714
Aminopyralid + triclopyr	0.991	0.532	−0.221	0.988	0.401	−0.809	1.000	0.917	0.420
Flumetsulam	−0.096	−0.070	0.111	−0.736	−0.332	−0.545	0.504	0.556	0.691
Thifensulfuron methyl	−0.003	−0.067	0.018	−0.488	−0.554	−0.477	0.529	0.562	0.804
MCPA	0.199	0.084	0.061	0.039	−0.332	−0.922	0.752	0.612	0.781
MCPB	−0.143	−0.106	−0.049	−0.606	−0.692	−0.824	0.541	0.445	0.721
MCPB + bentazone	−0.157	−0.072	0.050	−0.606	−0.554	−0.470	0.355	0.451	0.781
MCPA + MCPB	0.199	0.084	0.061	0.039	−0.332	−0.922	0.752	0.612	0.781
Flumetsulam + bentazone	−0.096	−0.070	0.111	−0.736	−0.332	−0.545	0.504	0.556	0.691
Flumetsulam + MCPA + MCPB	0.199	0.084	0.061	0.039	−0.332	−0.922	0.752	0.612	0.781

reduced by the mowing (Bourdôt et al. 2019). There is also evidence for an interaction between herbicide and mowing at 2 and 19 months after treatment ($P = 0.003$ and $P < 0.0001$ respectively), a result due to the generally higher covers of clover in the mowing treatment.

There is also strong evidence for an effect of herbicide on the clover ($P < 0.0001$) (Table 1) confirming earlier results (Lusk et al. 2011). The effect is characterised by a complete but temporary loss of clover cover at 2 months after treatment with aminopyralid and aminopyralid + triclopyr. Smaller reductions, as compared to the not-treated control, occurred with MCPA and thifensulfuron methyl, and increases occurred with flumetsulam, MCPB, and MCPB + bentazone. These effects lessened with time so that by 31 months after the herbicides had been applied, there was little difference in clover cover between any of the herbicide-treatments and the non-treated control (Table 1). Also evident is that the rate at which the clover returned varied between the herbicides with a slower recovery from aminopyralid and aminopyralid + triclopyr than with MCPA.

For the net benefit model, the mean, upper and lower quartile proportional reductions in the clover content (% cover) due to the herbicide treatment relative to the control without pre-graze mowing were calculated (Table 2). The large variation between herbicides in their effects on clover (ranging from a mean loss of 99% to an increase of 20% at 12 months after application) is evident.

Pasture foregone due to the presence of R. acris

The first step in developing the net economic benefit model was to determine the amount of pasture available for animals to consume that is foregone due to the presence of *R. acris*. Since the weed is avoided by dairy cows (Harper and Sagar 1953), the logic applied is that the land area in a pasture occupied by *R. acris* represents an equivalent loss in pasture dry matter yield (Bourdôt et al. 2003). This idea is supported by the 1:1 replacement of *R. acris* by grasses and clovers when an infested pasture is treated with any of the phenoxy carboxylic acid, ALS-inhibitor or pyridine carboxylic acid herbicides (Bourdôt et al. 2019). These observations suggest that the loss, L, in annual pasture dry matter yield of a paddock due to *R. acris* (tonnes pasture dry matter /ha/year) can be given as:

$$L = \frac{C}{(100 - C)} \times DM \tag{1}$$

where C is the average annual ground cover of the weed in the paddock (as a percentage of the total area of the paddock) in the absence of a control programme and DM is the total annual dry matter yield of the pasture (tonnes/ha/year) from the infested paddock. The loss in pasture dry matter yield preventable by an herbicide treatment would then be the sum of L across all years that the treatment exerts control of the weed, discounted by any direct losses in pasture dry matter through herbicide damage to clovers (Enriquez-Hidalgo et al. 2015; Chapman et al. 2017; Bourdôt et al. 2019). We develop this idea further in the following section.

Net economic benefit model

The net benefit model (Equation (2)) expands upon Equation (1). It gives the net benefit ($/ha) over the three years following an herbicide application as the monetary value of the extra milksolids produced over the three years (resulting from the utilisation of extra pasture dry matter produced in the space vacated by the *R. acris* following herbicide treatment) minus the costs of the treatment, including the cost of losing nitrogen-fixing clovers from herbicide damage.

The equation for the net economic benefit is:

$$\textit{Net Benefit over three years} = \left\{\left\{\begin{array}{l}\left[\left(\frac{C}{100-C}\right)\times\left(\frac{PE\times 1000}{Con}\right)\times\left(\frac{E_1}{100}\right)\right]+\\ \left[\left(\frac{C}{100-C}\right)\times\left(\frac{PE\times 1000}{Con}\right)\times\left(\frac{E_2}{100}\right)\right]+\\ \left[\left(\frac{C}{100-C}\right)\times\left(\frac{PE\times 1000}{Con}\right)\times\left(\frac{E_3}{100}\right)\right]\end{array}\right\}\times U\times MSPrice\right\} - (Costs) \quad (2)$$

where C is % cover of the giant buttercup in the paddock prior to spraying as in Equation (1); PE is the pasture dry matter (DM) eaten in the *R. acris*-infested paddock prior to spraying (tonnes DM/ha/y); Con is the rate of conversion of pasture dry matter eaten into milksolids (MS) (kg DM/kg MS); E is the reduction (%) in the % cover of the *R. acris* in the first, second and third years after spraying as compared to the cover without spraying (Bourdôt et al. 2019); U is a 'utilisation' parameter for the potential extra pasture DM eaten; $MSPrice$ is the price received for milksolids ($/kg); $Costs$ is the cost ($/ha) of the herbicide treatment (herbicide + adjuvant + application) plus the cost of clover damage caused by the herbicide (Equations (3–5)).

The net benefit model assumes the cover of *R. acris*, C, is measured in May before grazing and before the intended herbicide application. The cover of the weed in May closely approximates the average annual cover (Bourdôt et al. 2003) as required in the net benefit model (Equation (2)). The model assumes that the cover of *R. acris* in the pasture would not increase if the herbicide were not applied, resulting in a conservative estimate of the Net Benefit in the case of an increase.

Accounting for loss in clover (cost) due to herbicide damage

Reduction in the amount of clover in the pasture results in less fixed nitrogen (N) for pasture growth and reduced feeding value of the pasture, the latter describing the grazing animal response per unit of total forage available (Ulyatt 1981). Both have an associated monetary cost. The former can be equated to the cost of N fertiliser that would be required to replace the N fixed by clover. Similarly, the loss in pasture feeding value can be equated to the cost of the milksolids production foregone due to the reduction in clover content of the pasture. The sum of these two costs, for a particular herbicide, is the cost of the clover lost due to the use of that herbicide (Equation (5)).

The first step in estimating the cost of losing clover in a pasture due to damage from an herbicide is to calculate its $ value prior to the intended herbicide application. The second step is to multiply this value by the proportional reduction in the clover content caused by the herbicide. These steps are explained in detail in the remainder of this section using the example of a pasture where 12 tonnes of dry matter are eaten/ha/year, 15% of which is clover.

To estimate the cost of replacing the N fixed by the clover with N fertiliser (the monetary value of the clover), we assume that 60 kg N is fixed per tonne of clover dry matter (Chapman et al. 2018). The annual per ha cost of replacing the clover in our example pasture with a fertiliser containing 46% N by weight and costing \$575 per tonne applied, is then

$$Cost\ of\ N\ fertiliser = \left(12 \times \frac{15}{100}\right) \times 60 \times \left[\frac{\left(\frac{575}{1000}\right)}{\left(\frac{46}{100}\right)}\right] = \$135 \tag{3}$$

Equation (3) is scalable to an individual farm paddock in the decision tool (Bourdôt et al. 2020) where the user can provide paddock- or farm-specific values for pasture dry matter eaten per year, the clover content of the pasture, and the price and %N content of the N fertiliser.

To estimate the cost of milksolids production foregone if all the clover was lost from the pasture, we assume that there is a positive relationship between clover content in a grazed pasture and milk production per cow (Riberio Filho et al. 2003; Cosgrove et al. 2006; Egan et al. 2018). Supporting this idea, in a meta-analysis of published studies comparing milk production and yield from grass-only swards (GO) and grass/clover mixtures (GC), Dineen et al. (2018) determined that, at the mean clover content of GC swards included in the 35 comparisons that met the requirements of the analysis (31.6% of total pasture dry matter), milksolids (MS) yield was significantly greater in GC than GO (+120 g MS/cow/day). Further, there was a linear relationship between clover content and milk production across the full range of white clover content recorded in the eligible studies (Dineen et al. 2018). Thus, each 1% change in clover content was associated with a change in MS yield/cow/day of 3.75 g which scales to 1.01 kg MS per cow over a typical 270-day lactation. For our 15% clover scenario, and taking the New Zealand average stocking rate in 2019/2020 of 2.84 cows/ha (LIC and DairyNZ 2021), the effect of removing all of the clover from the pasture equates to a reduction of 43 kg MS/ha over a 12-month period. The economic cost of this is estimated by multiplying the production foregone by the MS price received by farmers. For the 15% clover scenario, applying the 2019/2020 milk price paid to owner-operators of \$7.05/kg MS (DairyNZ 2021), the economic cost of foregone milk production is \$304/ha (Equation (4)).

$$Cost\ of\ MS\ foregone = \left(15 \times \frac{3.75}{1000} \times 270 \times 2.84\right) \times 7.05 = \$304 \tag{4}$$

Like Equation (3) for the cost of replacing the clover with N fertiliser, Equation (4) giving the cost of milksolids foregone if all the clover was removed, is scalable in the decision tool (Bourdôt et al. 2020) and generalises to

$$Cost\ of\ MS\ foregone = \left(\%WC \times \frac{3.75}{1000} \times DIM \times SR\right) \times MSPrice$$

where $\%WC$ is the clover content in the pasture prior to treatment; DIM is the average herd lactation length expressed as days in milk per year; SR = stocking rate in cows/ha; $MSPrice$ is the milk price in units of $/kg milksolids. Farmers generally know their lactation length and stocking rate, and milk price can be chosen to reflect current or expected price trends.

The value of the clover in our example pasture is given by adding Equations (3) and (4);

$$\$135 + \$304 = \$439/\text{ha/year } (\$1317/\text{ha over three years}).$$

Now that we have the value of the clover in our pasture, we can consider the effect of an herbicide. We account for herbicide damage using the herbicide-specific proportional losses in clover given in Table 2. Using aminopyralid as an example (Equation 5), the mean per ha cost of the loss in clover over the three years following application of this herbicide is:

$$\begin{aligned} \textit{Cost of lost clover } [\textit{aminopyralid}] &= (439 \times 0.994) + (439 \times 0.555) \\ &\quad + (439 \times 0.015) \\ &= (436 + 244 + 7) = \$687. \end{aligned} \tag{5}$$

Upper and lower quartile values are calculated in the same way using the upper and lower quartile values for the proportional losses in clover from Table 2.

Example calculation of mean net economic benefit

We now present a worked example for the mean net economic benefit (Equation (2)) for an application of the herbicide aminopyralid to a dairy pasture. We assume an infestation of *R. acris* occupying 11.2% of the pasture in May prior to application and an annual average clover content of 15% of the pasture dry matter. The complete list of parameters and their values for this example is in Table 3.

Combining Equations (3) and (4), the value of the clover in this example pasture (as calculated above) in units of $/ha/year is:

$$\begin{aligned} \textit{Clover value} &= \left[\left(12 \times \frac{15}{100}\right) \times 60 \times \frac{\left(\frac{575}{1000}\right)}{\left(\frac{46}{100}\right)} \right] + \left(15 \times \frac{3.75}{1000} \times 270 \times 2.84\right) \times 7.05 \\ &= \$439 \end{aligned}$$

Table 3. Parameter values used in the example mean net benefit calculation for the herbicide aminopyralid.

Parameter	Symbol	Value
Equation 2 (Net Benefit)		
% cover of giant buttercup	*C*	11.2
Pasture eaten (t DM/ha/y)	*PE*	12
Pasture conversion to milksolids (kg DM/kg MS)	*Con*	13
Pasture utilisation (proportion)	*U*	0.8
Milk solids price ($/kg)	*MSPrice*	7.05
Herbicide cost ($/ha)	*Costs*	187
Herbicide application cost ($/ha)	*Costs*	35
Fertiliser product cost ($/t applied) e.g. Urea	*Costs*	575
Fertiliser product nitrogen content (% N by weight)	*Costs*	46
Herbicide efficacy year 1 (% decrease in *R. acris*)	*E1*	86.6
Herbicide efficacy year 2	*E2*	70
Herbicide efficacy year 3	*E3*	66.9
Clover reduction year 1 (relative to control)	*Costs*	0.994
Clover reduction year 2	*Costs*	0.555
Clover reduction year 3	*Costs*	0.015
Cost of lost clover year 1 (439 × 0.994)	*Costs*	436
Cost of lost clover year 2 (439 × 0.555)	*Costs*	244
Cost of lost clover year 3 (439 × 0.015)	*Costs*	7
Equation 3 (Cost of N fertiliser)		
N fixed by clover (kg N/t clover dry matter)	Constant	60
Equation 4 (Cost of MS foregone)		
Clover content (% of pasture DM eaten)	*%WC*	15
Rate of change in MS yield/cow/day/percent change in clover content of pasture (MS yield/cow/day)	Constant	3.75
Herd lactation length (days in milk/year)	*DIM*	270
Stocking rate (cows/ha)	*SR*	2.84

The mean net economic benefit, using Equation (2), is then:

$$Mean\ Net\ Benefit,\ Aminopyralid\left(\frac{\$}{ha}\ over\ three\ years\right) =$$

$$\left\{\left\{\begin{array}{l}\left[\left(\frac{11.2}{100-11.2}\right)\times\left(\frac{12\ \times 1000}{13}\right)\times\left(\frac{86.6}{100}\right)\right]+\\ \left[\left(\frac{11.2}{100-11.2}\right)\times\left(\frac{12\ \times 1000}{13}\right)\times\left(\frac{70}{100}\right)\right]+\\ \left[\left(\frac{11.2}{100-11.2}\right)\times\left(\frac{12\ \times 1000}{13}\right)\times\left(\frac{66.9}{100}\right)\right]\end{array}\right\}\times 0.8\times 7.05\right\}$$

$$-(187+35+436+244+7)=\ \$559$$

To calculate the likely range in the net benefit (not presented here), the upper and lower quartile values for the proportional loss in clover (Table 2) are used to calculate the clover loss costs for year 1, year 2 and year 3 (replacing the mean costs of 436, 244 and 7, respectively, with their upper and lower quartile counterparts). Similarly, the herbicide efficacy values for year 1, 2 and 3 (86.6, 70 and 66.9) are also replaced with their upper and lower quartile values (Bourdôt et al. 2019).

Simulations

The net economic benefit model (Equation (2)) was simulated in Excel to explore the relationship between the net economic benefit and the cover of *R. acris* in a pasture typical of a Golden Bay dairy farm for each of the herbicides aminopyralid, aminopyralid + triclopyr, flumetsulam, thifensulfuron methyl, MCPA, MCPB and MCPB + bentazone. The 'Goal Seek' function in Excel was used to derive the 'breakeven' ground covers of *R. acris* for each of the herbicides. The modelled pasture was assumed to produce 12 tonnes eaten dry matter per hectare per year (*PE* in Equation (2)) over a range of *R. acris* infestation levels from 1 to 16% ground cover (*C* in Equation (2)). The pasture dry matter was assumed to be converted by the cows in the herd to milksolids at the rate of 13 kg pasture dry matter per 1.0 kg milksolids (*Con* in Equation (2)). The utilisation rate for the extra pasture produced following herbicide treatment was set at 80% (*U* in Equation 2), a value giving a desired springtime post-grazing residual of 1500–1600 kg pasture dry matter/ha/year in a typical pasture (DairyNZ 2021). The milksolids price was set at $7.05 per kg. Herbicide efficacies (E_1, E_2 and E_3 in Equation (2)) were taken from Figure 4 in Bourdôt et al. (2019) and the clover content and costs of clover damage were modelled as in Equations (3) and (4). Herbicide costs were 2019 values (Bourdôt et al. 2020).

Web application

A web application, Giant Buttercup Management Decision Support, deploying the net economic benefit model (Equation (2)) as a decision-making tool for managing *R. acris* in a dairy pasture, has been published (Bourdôt et al. 2020).

Results and discussion

The results are presented as plots of the mean, and upper and lower quartile estimates of the net monetary benefit ($/ha/three years) against the pre-treatment percentage ground cover of the *R. acris* (Figure 1). For each of the herbicides, the net economic benefit (i.e. profitability) increases with the pre-treatment cover of *R. acris*. This is the result of the additional pasture dry matter produced within the paddock, due to the reduction in the cover of *R. acris*, and its conversion to milksolids as per Equation (2). Also evident in these simulation results is that the net benefit for aminopyralid and aminopyralid + triclopyr increases more steeply with *R. acris* cover, and the breakeven *R. acris* cover is higher, than for flumetsulam, thifensulfuron methyl, MCPA, MCPB and MCPB + bentazone (Figure 1). The steeper increase in net benefit is a result of the greater and more durable reduction in the cover of the weed afforded by aminopyralid and aminopyralid + triclopyr (Bourdôt et al. 2019). The higher breakeven covers for aminopyralid (C_{BE}=7.24) and aminopyralid + triclopyr and aminopyralid + triclopyr (C_{BE}=5.72) compared to flumetsulam (C_{BE}=1.88), thifensulfuron methyl (C_{BE}=1.50), MCPA (C_{BE}=3.72), MCPB (C_{BE}=−0.88) and MCPB + bentazone (C_{BE}=1.51) is the result of their higher cost per ha (data not given here) combined with their greater and longer-lasting impact on the N-fixing clovers in the sward (Tables 1 and 2). The results suggest that on average, higher profits are likely from aminopyralid and aminopyralid + triclopyr than from the other herbicides so long as the cover of *R. acris* is above 6–7%; losses are predicted, on average, for lower *R. acris* covers (Figure 1).

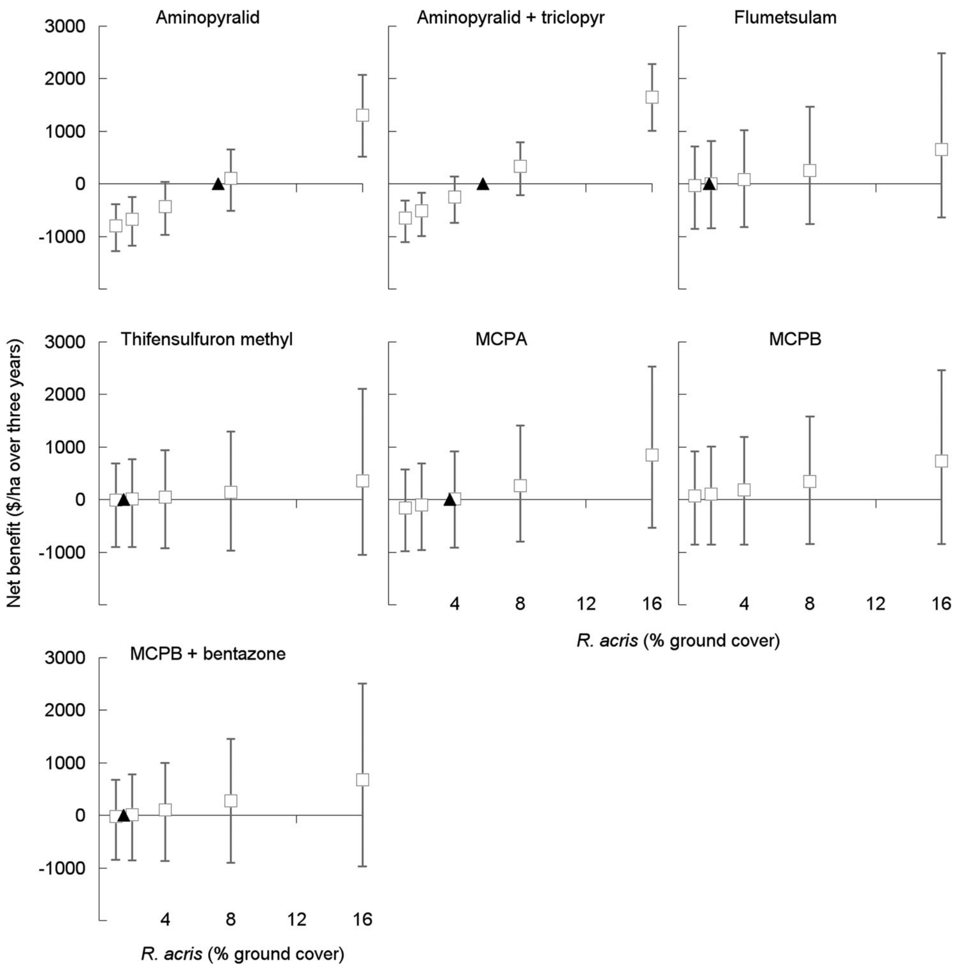

Figure 1. Modelled net economic benefits for herbicide treatments applied to control *Ranunculus acris* in a dairy pasture at 1%, 2%, 4%, 8% and 16% pre-treatment ground cover, *C*, of the weed (means [open square symbols] with upper and lower quartiles). The simulations use Equation (2) with parameters representing a typical dairy pasture in the Golden Bay district, Tasman Region, New Zealand, as described in the text. Mean breakeven ground cover percentages, C_{BE}, are indicated by the filled triangles: aminopyralid $C_{BE} = 7.24$; aminopyralid + triclopyr $C_{BE} = 5.72$; flumetsulam $C_{BE} = 1.88$; thifensulfuron methyl $C_{BE} = 1.50$; MCPA $C_{BE} = 3.72$; MCPB $C_{BE} = -0.88$ (not drawn); MCPB + bentazone $C_{BE} = 1.51$.

The anomalous negative breakeven cover of *R. acris* for MCPB, −0.88%, in the above analysis indicates a positive net economic benefit from applying this herbicide when there is no *R. acris* in the pasture. This comes about because of the substantial increases in clover content of the dairy pastures in our experiment (Bourdôt et al. 2019). These increases averaged 14%, 11% and 5% in years 1, 2 and 3 after treatment (Table 2) and can be explained by the combined effects of MCPB being non-toxic to clovers and, we presume, by it controlling competitors in the sward in addition to *R. acris*.

The third feature of these simulated net economic benefits is their considerably higher variability in the case of flumetsulam, thifensulfuron methyl, MCPA, MCPB and MCPB

+ bentazone than for aminopyralid and aminopyralid + triclopyr (Figure 1). This is a direct result of the greater variability in the efficacy of the phenoxy carboxylic acid and ALS-inhibitor herbicides as compared to the pyridine carboxylic acids (Bourdôt et al. 2019). We hypothesise that this greater variability is due, at least in part, to evolved resistance to the phenoxy carboxylic acid and ALS-inhibitor herbicides and its spatial variability that has resulted from variable herbicide use histories (and hence variable selection pressure) at farm and paddock scales (Bourdôt et al. 1990a; Lusk et al. 2015). To explore this idea further, we reanalysed the efficacy data presented in Table 2 of our previous paper (Bourdôt et al. 2019) to partition the variance (in the reduction in % cover of *R. acris*) into the categories 'between farms', 'between paddocks with farms' and 'within paddocks' (Table 4). This analysis reveals that the variance explained is, for each of these three partitions, more than two-fold greater for the phenoxy carboxylic acid and ALS-inhibitor herbicides as compared to the pyridine carboxylic acids (Table 4). This result is consistent with our hypothesis, the reported cases of resistance to the phenoxy carboxylic acid and ALS-inhibitor herbicides, and the assumption that resistance is unlikely to have evolved to the pyridine carboxylic acids since they have only recently become available in New Zealand as herbicides for weed control in pastures.

The variation in profitability of each of the herbicides (Figure 1) provides a basis for accounting for historical herbicide exposure and possible resistance in the decision-making regarding the appropriate herbicide for a specific *R. acris*-infested dairy pasture. For example, if the pasture modelled here was known to have been treated repeatedly in the past with MCPA and flumetsulam, and/or these herbicides had performed poorly in recent applications, resistance to both these mode-of-action classes may be evolving. The further along this evolutionary pathway the *R. acris* population has progressed, the less will be the efficacy of the herbicide and the lower will be the economic benefit (profit) from using it again. If this pasture had 16% cover of *R. acris*, our simulation indicates that the realised net benefit from MCPA lies somewhere between \$2531/ha/three years (the upper quartile) and -\$534/ha/three years (the lower quartile) (Figure 1). Similarly, for flumetsulam the net benefit lies somewhere between \$2488/ha/three years (the upper quartile) and -\$634/ha/three years (the lower quartile) (Figure 1). In this case, given there is a risk of not breaking even, a risk-averse stance would be to apply aminopyralid or aminopyralid + triclopyr instead where, at 16% cover of *R. acris*, the realised net benefit is positive and lies between \$2072 and \$525/ha/three years (Figure 1).

Table 4. Partition of variance in the reduction in the % ground cover of *R. acris* due to 'between farm', 'between paddocks within farms' and 'within paddocks' as originally presented in Figure 4 in our field experiment report (Bourdôt et al. 2019).

Herbicide	Mode of action group	Between farms	Between paddocks within farms	Within paddocks
Aminopyralid	Pyridine carboxylic acid	18	51	66
Aminopyralid + triclopyr	Pyridine carboxylic acid	16	38	59
Flumetsulam	ALS-inhibitor	42	125	136
Thifensulfuron methyl	ALS-inhibitor	36	98	127
MCPA	Phenoxy carboxylic acid	53	95	127
MCPB	Phenoxy carboxylic acid	7	111	119
MCPB + bentazone	Phenoxy carboxylic acid	41	88	141

If the pasture modelled here was known to have no history of MCPA or flumetsulam use, or these herbicides had been used only sporadically in the past and rotated, then resistance to either would be unlikely. In this case, where the cover of *R. acris* is 16%, the realised net benefit is likely to approach or exceed the upper quartile values of $2531 and $2488/ha/three years for MCPA and flumetsulam, respectively (Figure 1) and either herbicide is likely to be profitable.

The methodology developed here for determining if a *R. acris* infestation in a dairy pasture can be controlled profitably using an herbicide is available as the web application at https://giant-buttercup-ds-tool.azurewebsites.net/.

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Data availability

Data used to construct the figure in this article are available from corresponding author upon reasonable request. They can be generated at https://giant-buttercup-ds-tool.azurewebsites.net/.

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