Giant buttercup (*Ranunculus acris*) management in dairy pastures – herbicides

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CONTENTS

1. EXECUTIVE SUMMARY

- AgResearch has been contracted by Dairy NZ (Schedule number OF1001) to review scientific and technical information on the use of herbicides as management tools for giant buttercup in dairy pastures in New Zealand and to summarise this information in a written report to the Giant Buttercup Management Group based in Takaka. This review is part of a larger project aimed at providing options for dairy farmers to achieve control of this weed.

- A literature search was conducted to find published papers and unpublished reports on the topic. The information was critically reviewed and the key findings are discussed in this report.

- The key findings from this review are:

    - Pasture herbicides with known activity against giant buttercup (in New Zealand Europe, Canada and USA) fall into seven different "mode-of-action" groups providing some scope for developing herbicide rotations that would avoid or slow up the evolution of herbicide resistance.

    - All of these "pasture" herbicides are toxic to aquatic organisms and some are toxic to terrestrial invertebrates, pasture grasses and clovers.

    - Giant buttercup is a suitable target for wick or wiper application of herbicides that cannot be sprayed on pasture due to their toxicity to grasses and/or clovers since it is not eaten by dairy cattle and thus stands well above the residual grass and clover after grazing. Metsulfuron, chlorsulfuron, glyphosate, picloram and aminopyralid have potential for use against giant buttercup in pasture in this way.

    - The efficacy of pasture herbicides for controlling giant buttercup is likely to be greater when the other pasture species are growing vigorously as might be ensured by timely and appropriate fertiliser application.

    - Forage cropping on dairy farms opens up a wide range of additional herbicides some of which may be effective against giant buttercup. Many of these herbicides are in mode-of-action groups different from those registered for application to pasture thus widening the scope for developing herbicide rotations for herbicide resistance management.

- This report should be read along with the others (Hurrell & Bourdôt 2011; King & Rennie 2011) from the project as a basis for discussions on how to manage giant buttercup on dairy farms in the Golden Bay region.

2. BACKGROUND

The Giant Buttercup Management Group, based in Takaka, was successful in securing an On Farm Innovation Fund Grant from Dairy NZ in 2010 (Schedule number OF1001) to conduct "Stage One" of a project on giant buttercup in dairy pastures. Stage One will identify options for controlling the weed, including the economics of doing so, and thereby provide the foundation for "Stage Two" which will evaluate the options and develop best management practice.

The objective of the project overall is to provide dairy farmers with tools and information enabling them to return dairy pastures affected by the weed giant buttercup (*Ranunuculus acris*) to full grass production. To this end Stage One of the project aims to:

1. further develop the biological "mycoherbicide" methodology to a stage where it offers an effective and readily available product, and

2. collate information about existing and potential new chemical control options and deliver these options to farmers as clear and freely available information.

3. quantify the economic benefit from control of giant buttercup on a dairy farm.

The current report fulfils the requirements of (2) above, and specifically, as per the agreement with Dairy NZ, provides a "*Collation of current chemical control options providing information on chemical and brand names, grouping by 'mode of action' to provide farmers with information to help avoid and manage herbicide resistance. This research will include weed-wiper and similar technologies for achieving selective control using herbicides that cannot be sprayed on pasture, herbicides not yet available or registered for use against giant buttercup in New Zealand, and the likely effects of these options on pasture and the environment*."

3. METHODS

Two international literature searches were conducted. The first focussed on finding published studies dealing with the effectiveness of chemical herbicides against giant buttercup. The search utilised CAB Abstracts, Biosis, Scopus, Agris and GoogleScholar, the search terms "giant buttercup", "meadow buttercup", "tall buttercup", "*Ranunculus acris"*, and "herbicide", and was restricted to the period 2006 to the present day. The publications found were combined with those from an earlier search on the same topic (Lamoureaux & Bourdôt 2007) which covered the period from 2006 back to first-available records. The mode-of-action group for each of the herbicides found to have some effect on giant buttercup was ascertained from the New Zealand Committee on Pesticide Resistance listing of herbicide products available in New Zealand (NZCPR 2009). Information on the registration status of each of the herbicides in New Zealand, their environmental safety, application rates and other label claims relevant to this report were ascertained from the NZ Novachem Agrichemical Manual (Young 2010).

The second literature search focussed on finding published studies dealing with application methods for non-selective herbicides in pastures. This search also utilised CAB Abstracts, Biosis, Scopus, Agris and GoogleScholar. The search terms used were "giant buttercup", "meadow buttercup", "tall buttercup", "*Ranunculus acris"*, "weed wiper", "wiper", "carpet roller", "weed swiper", "roto wiper", and "Eliminator". No date restriction was applied to this search enabling it to find published articles from the first-available records up to the present day.

The findings from the scientific and technical articles, reports and web-sites found by the two searches and from Lamoureaux & Bourdôt (2007) are reviewed and summarised in the remainder of this report within the context of part (2) of the Objective of the project.

4. RESULTS AND DISCUSSION

The first literature search along with the earlier review by Lamoureaux & Bourdôt (2007) identified a variety of information sources pertaining to chemical herbicides and their use against giant buttercup. By contrast, the second search, pertaining to application methods for non-selective herbicides in pastures, returned relatively few information sources.

4.1 Herbicides known to be effective against giant buttercup

The herbicides that have shown some activity against giant buttercup in New Zealand and overseas (Europe, Canada, USA) fall into seven different “mode-of-action” groups. These groupings reflect the bio-chemical mechanism by which the herbicide damages the weed and, as discussed in Section 4.2, provide a way of avoiding or slowing up the evolution of herbicide resistance in weed populations.

Group B

Herbicides in this group act by inhibiting acetolactate synthase (ALS), blocking the biosynthesis of the branched-chain amino acids valine, leucine and isoleucine. This inhibition leads to the rapid cessation of plant cell division and growth. Four herbicide active ingredients in this group are known to have herbicidal activity towards giant buttercup (Table 1). Two of these, flumetsulam and thifensulfuron-methyl, have New Zealand product label claims for giant buttercup (Preside and Valdo 800WG) and (Harmony, Backup, Ranger and Chord) respectively. The label recommendation for both Preside and Valdo 800WG is to boom-spray at 65g/ha before flowering with the addition of a suitable spraying oil (Young 2010). Repeat treatment for two successive springs is recommended in both cases. Harmony, Backup, Ranger and Chord have a recommended rate for boom-spraying of 20 - 30g/ha for applications in spring - repeat applications may be necessary.

Flumetsulam is highly toxic to aquatic plants and requires a withholding period of 14 days before allowing stock back on to the treated pasture. It has little or no effect on clovers (Harris & Husband 1997). Thifensulfuron-methyl has a withholding period of 7 days and is as ecotoxic as flumetsulam.

It is reasonable to predict that the usefulness of flumetsulam against giant buttercup may persist for only a few years. Being an ALS (acetolactate synthase) inhibitor, it has a mode-of-action to which many weed species around the world have rapidly evolved resistance (Llewellyn & Powles 2001) (see Section 4.2).

Products containing thifensulfuron-methyl typically damage the grasses and clovers (Sanders et al. 1994; Harris & Husband 1997). The clovers may take up to 4 months to recover (Young 2010), reducing the competitiveness of the pasture and, as a result, potentially promoting the recruitment of *R. acris* seedlings (Tuckett 1961; Lusk et al. 2009). The two products containing flumetsulam, by contrast, do not damage grasses or clovers.

The two other ALS inhibitors that have been shown to have activity towards giant buttercup are metsulfuron and chlorsulfuron in the USA-registered products (Escort and Ally) and Telar respectively (Table 1). These two active ingredients are registered in New Zealand in products with label claims for scrub weeds and weeds in cereals respectively. However neither has a label claim for giant buttercup and neither has apparently been tested on giant buttercup in New Zealand.

Metsulfuron (in all of its various products) is extremely injurious not only to aquatic organisms but also to ryegrass/white clover pasture with soil residues preventing pasture re-establishment for at least 3 months (Young 2010). Nevertheless, metsulfuron may potentially be safely applied to giant buttercup in a pasture with careful use of a carpet roller/wiper applicator. Buttercups in general have a label claim for this use (Young 2010). This method of application is discussed in more detail in Section 4.3.

Group C3

Herbicides in this group act by inhibiting Photosystem II, a key part of the photosynthesis process in plants. They typically result in burning of the leaves contacted by the herbicide and yellowing of older leaf margins. The only herbicide in this group known to have activity against giant buttercup is bentazone. This herbicide (in the product Basagran) (Table 1) has a New Zealand label claim for use on giant buttercup in pasture (Young 2010). The label recommendation is to remove the stock from the paddock to be treated for 5-10 days, then apply MCPA at 4 litres product/ha, followed 1-5 days later with Basagran at the rate of 0.75 litres/ha. This recommendation is based on field trials conducted in Takaka by Lincoln University (Butcher et al. 1993).

Bentazone is also available in New Zealand in mixture with MCPB in the product Pulsar (Table 1) but this product does not have a label claim for giant buttercup.

Bentazone is harmful to aquatic organisms but does not damage pasture grasses or clovers (Young 2010). By contrast, MCPA is highly toxic towards clovers.

Group E

Herbicides in this group act by inhibiting protoporphyrinogen oxidase (PPO) resulting in cell membrane disruption in susceptible plants. Susceptible plants exhibit burning of the leaves. The only herbicide in this group known to have activity against giant buttercup is oxidiazon (in the product Foresite) (Young 2010). This is a pre-emergence herbicide for the control of grass and broadleaved weeds in stonefruits, vineyards, other woody crops and onions. It is applied at 2-4 litres/ha to bare moist soil and is taken up from the soil by emerging weed shoots. It is not suitable for application to pasture.

Oxidiazon is toxic to aquatic organisms and the soil environment (Young 2010).

Group G

Herbicides in this group inhibit EPSP synthase thereby inhibiting the synthesis of amino acids. They result in yellowing of the new growth of susceptible plants leading to browning and death. The only herbicide in this group known to have activity against giant buttercup is glyphosate (in many difference products containing 360, 450 or 510 g glyphosate/litre) (Young 2010). No glyphosate-based product available in New Zealand has a label claim for giant buttercup but all have claims for use in pasture renovation (to kill the existing sward) (Young 2010).

An experiment in New Zealand demonstrated that giant buttercup is susceptible to glyphosate (Thompson 1983). The West Coast Regional Council in New Zealand also claims that glyphosate is effective against giant buttercup (Trayes & Belton 2010) as does Shaw (2010) in Washington, USA.

Glyphosate is toxic to aquatic organisms with long-lasting effects (Young 2010).

Group O1

Herbicides in this group are synthetic auxins (plant growth regulators) in the chemical family phenoxy carboxylic acids. They interfere with cell division and growth and result in bending and twisting of leaves and stems, symptoms often evident almost immediately after application. Delayed symptom development may include root formation on stems, deformed leaves, stems and flowers, and abnormal roots. Only one of these “phenoxys” (MCPA) has a New Zealand label claim for giant buttercup and one other, MCPB, has a NZ label claim for “perennial buttercups” but not specifically for giant buttercup. These two herbicides occur in a wide variety of products (Table 1) differing only by product name, proprietor and in some cases concentration and or formulation of the active ingredient (Young 2010).

MCPA is produced in two formulations; potassium salt products at 375 g MCPA/litre (MCPA Potassium 375), and dimethylamine salt products at 500, 720 and 750 g MCPA/litre (e.g. Agritone 750, Agpro 750 and Maestro). Products containing 375 g MCPA/litre are recommended applied (with hydraulic nozzles) at 4 - 6 litres product / ha when the buttercup is at the early flower bud stage and when the plants are about 30-40 cm tall (Young 2010). The 500 g MCPA/litre product (Headland Spear) is recommended applied at 3-4.5 litres/ha for giant buttercup. Other products containing the dimethylamine salt formulation are recommended applied to giant buttercup at 1.5 – 3 litres product/ha, with the higher rate to be used on larger plants. Repeat annual treatment is acknowledged (on the product labels) as being necessary in some cases.

MCPB (in products containing 400 g MCPB / litre) is recommended applied (with hydraulic nozzles) at 6 litres product / ha (to perennial buttercups) first in the early summer and again in the autumn. A third application in the following summer is recommended.

These herbicides have no effect on grasses but cause damage in a wide range of broadleaved plants. In particular, MCPA is highly damaging to clovers. MCPB by contrast, has no effect on clovers.

Both MCPA and MCPB are highly toxic to aquatic organisms and to some terrestrial vertebrates.

Group O2

Herbicides in this group are also synthetic auxins but are in the chemical family benzoic acids. They too interfere with cell division and plant growth and result in bending and twisting of leaves and stems. The only “benzoic” available in New Zealand is dicamba and this occurs in several products (Table 1) for application to pastures in mixture with MCPA or 2,4-D at rates from 100 to 350 ml / ha . While dicamba does not have a NZ label claim for giant buttercup (Young 2010), it does have label claims for selective control of giant (tall) buttercup in pastures in the USA in the products Kamba and Clarity (BASF 2010; EPA 2010; Jacobs 2010).

Dicamba damages clovers and their re-establishment may be affected for several months (Young 2010).

Dicamba is very toxic to aquatic organisms and to terrestrial vertebrates and invertebrates (Young 2010).

Group O3
Herbicides in this group are also synthetic auxins but in the chemical family pyridine carboxylic acids. They too interfere with cell division and plant growth and result in bending and twisting of leaves and stems. No herbicide in this group has a NZ label claim for giant buttercup but two, aminopyralid and picloram (in products Milestone and ForeFront R&P respectively) have label claims for the control of giant buttercup (in rangeland and permanent grass pastures) in Canada and the USA respectively (DOW 2010b; EPA 2010).

Aminopyralid and picloram (available together in NZ in the product Tordon Brushkiller, and separately in Tordon Max and Tordon 2G respectively) are both highly toxic to clovers and other pasture legumes and prevent re-establishment of these pasture plants for at least 6 months after spraying (Young 2010).

Both herbicides are also harmful to aquatic organisms (Young 2010).

4.2 Herbicides known to be ineffective against giant buttercup

In field trials in Takaka in 1991-92 and 1992-93, the herbicides asulam (Asulox) and clopyralid (Versatill) had little effect on giant buttercup (Butcher et al. 1993). In addition, the herbicide ioxynil (Totril), a product registered for weed control in fine turf, onions and garlic, and 2,4-D butyl ester (2.4-D Ester 80EC), had little effect and were not evaluated in the field (Butcher et al. 1993).

Table 1. Herbicides with known useful activity towards *Ranunculus acris* (giant buttercup) and other buttercups

Chemical name	Product name(s)	Species susceptible	Country with label claim	Comments on use	Source	Mode of Action Group (NZCPR 2009)
Flumetsulam	Preside, Valdo 800WG	*R. acris*	NZ	Pasture herbicide	Young (2010), (Harris & Husband 1997)	B
Thifensulfuron-Methyl	Harmony, Backup, Ranger, Chord	*R. acris*	NZ	Pasture herbicide, damages clovers and grasses	Young (2010), Sanders (1994), Harris & Husband (1997)	B
Metsulfuron	Agmax Met 600, Agpro Meturon, Agronica metsulfuron, Associate 600 WDG, Donaghys Brushweed Kill Met600, Eradicate, Escort, Matrix WDG, Matrix WP, Mustang, Prism, Zeal, *Escort, Ally (USA)*	*R. acris*	USA	Pasture herbicide, damages clovers (carpet roller application recommended for use on buttercups in pasture)	Shaw (2010) ,Young (2010)	B
Chlorsulfuron	Agronica chlorsulfuron, Centric, Clenecorn, Colt, Glean, Tackle 750WDG, *Telar (USA)*	*R. acris*	USA	For cereal crops	EPA (2010)	B
Bentazone	Basagran	*R. acris*	NZ	Apply to pasture after MCPA	Young (2010)	C3
Bentazone / MCPB	Pulsar	Others	NZ	Pasture herbicide	Young (2010)	C3/O1
Oxadiazon	Foresite	*R. acris*	NZ	Pre-emergence herbicide for woody perennial crops.	Young (2010)	E
Glyphosate	Roundup (and many others in 360, 450 and 510g/l formulations) (Young 2010)	*R. acris*	None	Damages clovers and grasses	(Thompson 1983), Shaw (2010)	G
MCPA	Agritone 750, Agpro MCPA, Agpro MCPA 750, Clean Sweep, Donaghys Broadleaf Kill MCPA, Headland Spear, Maestro, MCPA	*R. acris*	NZ	Pasture herbicide, damages clovers	Young (2010), Tuckett (1961), Popay (1989), Popay (1984), Bourdôt (1990), Sanders (1994), Harris & Husband (1997), Butcher (1993)	O1

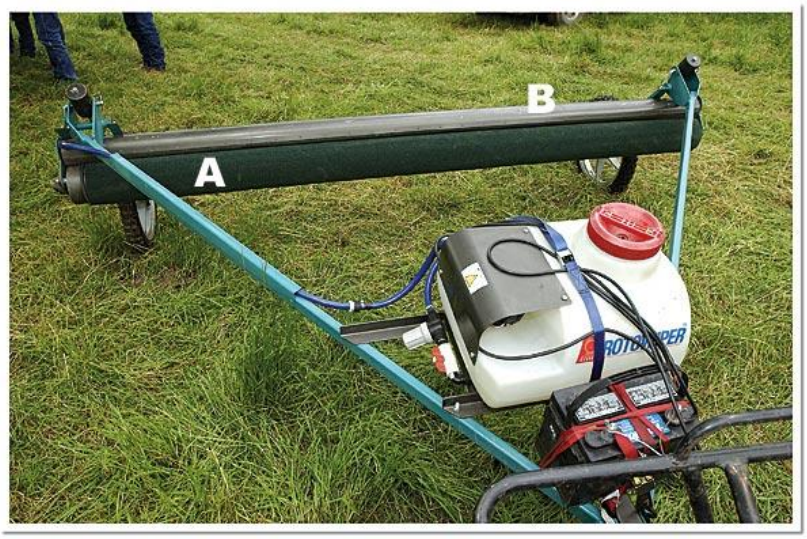
Chemical name	Product name(s)	Species susceptible	Country with label claim	Comments on use	Source	Mode of Action Group (NZCPR 2009)
	Amine 750, MCPA Potassium 375, Orion MCPA 750, Pasture Guard MCPA					
2,4-D amine	Donaghys Broadleaf	Others	NZ	Pasture herbicide, damages clovers	Young (2010)	O1
2,4-D ethylhexyl ester	Donaghys Broadleaf	Others	NZ	Pasture herbicide, damages clovers	Young (2010)	O1
2,4-DB	2,4-DB Herbicide	Others	NZ	Pasture herbicide, damages clovers	Young (2010)	O1
Mecoprop / Dichlorprop / MCPA	Duplosan Super	Others	NZ	Pasture herbicide, damages clovers	Young (2010)	O1
MCPB	Dow Agrosciences MCPB, Nufarm MCPB 400, Pasture Guard MCPB, Soft Touch	Others	NZ	Pasture herbicide	Young (2010)	O1
MCPB	Dow Agrosciences MCPB, Nufarm MCPB 400, Pasture Guard MCPB, Soft Touch	*R. acris*	None	Pasture herbicide	Thompson (1983), Popay (1989), Bourdôt (1990), Harris (1997)	O1
MCPA / MCPB	Select ,Thistrol Plus, Tropotox Plus	*R. acris*	NZ	Pasture herbicide, damages clovers	Young (2010)	O1/O1
2,4-D / dicamba	None	*R. acris*	None	Pasture herbicide	Thompson (1983)	O1/O2
2,4-D / picloram	None	*R. acris*	None	Pasture herbicide	Thompson (1983)	O1/O3
Dicamba	Banvel, Buttress, Cutlass, Dicam 480, Dicamba 500SL, Kamba 500, *Clarity (USA),*	*R. acris*	USA	Pasture herbicide, damages clovers	BASF (2010), Jacobs (2010), EPA (2010)	O2
Aminopyralid	*Milestone Herbicide (Canada)*	*R. acris*	Canada	Pasture herbicide, damages clovers	DOW (2010a), Jacobs (2010)	O3
Aminopyralid / 2,4-D	*ForeFront R&P(USA)*	*R. acris*	USA	Pasture herbicide, damages clovers	DOW (2010b)	O3/O1
Picloram / aminopyralid	Tordon Brushkiller	*R. acris*	None	Damages clovers	Young (2010), DOW (2010b)	O3/O3

4.3 Wiper application of herbicides in pasture

Herbicides with known activity against giant buttercup, but that are too damaging to pasture grasses and/or clovers to be boom-sprayed onto a dairy pasture, may be applied without (or with minimal) pasture damage using wiper technology. Two brands of weed wiper machines available in New Zealand are the “Rotowiper” and the “Eliminator” (C-Dax 2010; Rotoworks 2010) (see photos below). Essentially weed wipers allow an herbicide to be applied to weeds that stand above the height of the pasture (as after a recent grazing). Giant buttercup is a suitable target since it is not eaten by dairy cattle and therefore stands well above the residual grass and clover in a recently-grazed dairy pasture.

The key advantages of a weed-wiper in pasture are:

1. Enables selective control of the weed with a non-selective herbicide
2. Widens the range of herbicides that can be used in a pasture
3. Reduces the cost of herbicide application because only the weed is treated
4. Reduces the amount of herbicide in the environment



Rotowiper weed wiper. A: Counter-rotating drum. B: Hooded spray boom to wet drum surface (Rotoworks 2010)

Eliminator weed wiper with effective cover of 2.5m (C-Dax 2010)

Herbicides with potential to control giant buttercup in pasture using a weed wiper

1. **Metsulfuron**, available in the product Escort, and in many other products registered in New Zealand (Table 1) has potential to control giant buttercup in a pasture when applied with a wiper. It has the following label claim: *"Carpet Roller/Wiper applications: For control of Ragwort, buttercup, Scotch, Californian, winged and nodding thistles. Graze pasture to maximise height difference between pasture and weeds. Pre-mix 1 g/litre of water and ensure roller is wet before starting off. In heavy weed infestations a second pass in the opposite direction will provide best results. Keep the wiping area moist and free of debris. To prevent localised pasture damage avoid dripping from the roller/wiper."* (Young 2010). While metsulfuron does not have a label claim for giant buttercup in New Zealand (Table 1), it does have a label claim in the USA (Shaw 2010) indicating that it is effective against USA populations of giant buttercup. Since the giant buttercup present in the USA is almost certainly the same subspecies that we have in New Zealand (*Ranunculus acris* subsp *acris*), it is likely that this herbicide would be as effective in New Zealand as in the USA.

2. **Chlorsulfuron**, available in New Zealand in the product Glean and in several others (Table 1) may also be effective against giant buttercup in pasture when applied with a wiper. This herbicide does not have a NZ label claim for giant buttercup and is registered for use in cereals, not pasture. However, it does have a label claim for giant buttercup in the USA indicating that it is effective against the weed.

3. **Glyphosate**, available in the product Roundup, has the potential to control giant buttercup in a dairy pasture when applied with a wiper. It was tested in November 1982 in an experiment in which a 33% solution of Roundup (360 g glyphosate/litre) and water was applied in a double-pass in opposite directions at 3 km/h using a Winstones 2 m wide boom fitted with adjustable-flow wicks (Thompson 1983). The treatment gave a 75% reduction in giant buttercup. The authors stated "*Given the relatively lax grazing imposed on dairy pastures in spring, wick applicators can safely contact only the almost leafless flowers stalks of giant buttercup. Control with all herbicide (others tested were 2,4-D+picloram and 2,4-D+dicamba) was relatively poor but glyphosate gave best results.*"

4. **Picloram + aminopyralid**, available in New Zealand in the product Tordon Brushkiller, is likely to be effective against giant buttercup since the weed is known to be susceptible to both active ingredients. Aminopyralid has a label claim for the weed in Canada and in the USA (DOW 2010a, b; Jacobs 2010). Picloram (in combination with the relatively ineffective 2,4-D) gave 53% reduction in giant buttercup in an experiment in New Zealand in which it was applied with a wiper (Thompson 1983).

The above herbicides could usefully be tested and compared for efficacy against giant buttercup in a field experiment in dairy pastures. The protocol for such an experiment should include the factors considered in a recent experiment on Californian thistle (Moyo 2006, 2008; Moyo et al. 2008); these included speed, number of passes and time of year. Additional herbicides could be added to such an experiment, particularly those that have shown to be effective on other perennial weeds.

4.4 Herbicides combined with fertiliser in pasture

Chemical herbicides including paraquat, diquat, 2,4-D and MCPA have, in field experiments, reduced *R. acris* and fostered more nutritional species in deteriorated natural meadows in Czechoslovakia (Hrazdira 1970), Russia (Babenko 1991), Norway (Vidme 1973), Slovakia (Lackovic 1974) and in north western and central France (Delpech 1976). NPK fertilizers applied along with MCPA have reduced *R. acris* in deteriorated natural grasslands in Norway (Vidme 1973), Slovakia (Lackovic 1974) and Czechoslovakia (Hrazdira 1975). However, the success of these herbicides in managing *R. acris* in agricultural practice has generally not been reported although there has been at least one report from New Zealand where MCPA applied before an application of the fertiliser, Liquiphos, gave better control of the weed than when applied without the fertiliser follow-up (Mangatoki farmer Lindsay Morgan – Graham Ball *pers. com.*). An explanation for this effect is that the fertiliser promoted that growth of the grasses and clovers, enabling them to better outcompete the buttercup; in an experiment in Alberta, Canada, the greatest reductions in Californian thistle occurred when spring fertiliser applications to enhance forage vigour were combined with herbicide application (Bork et al. 2005). In this same study, fertiliser also decreased giant buttercup in the pasture – although the effect was not statistically significant (Bork et al. 2005).

The message from these studies is that the efficacy of herbicides used against giant buttercup is likely to be greater when the other pasture species are growing vigorously as might be ensured by timely fertiliser application.

4.5 Herbicides in crops

Opportunities exist on a dairy farm to use herbicides to control giant buttercup prior to and during the growth of forage crops (brassicas and cereals). Forage crops open up a wide range of additional herbicides that may be effective against giant buttercup, many of which are in mode-of-action groups different from those registered for us in pasture (Young 2010). Most of these have never been tested against giant buttercup. Many fall within mode-of-action groups different from those herbicides that can be used in pasture (Table 1) and so potentially increase a dairy farmer's scope for preventing or slowing the rate of herbicide resistance evolution in giant buttercup (see section 4.6).

4.6 Herbicide resistance and its management

The "phenoxy" herbicides MCPA and MCPB were historically relied upon by New Zealand dairy farmers for the control of giant buttercup. Whilst they gave good control during the early years following their introduction (in the late 1940s) (Tuckett 1961), by the 1980s it was evident from field trials that they were now not very effective on many dairy farms in both the north (Popay et al. 1984, 1989) and south Island (Bourdôt & Hurrell 1990). Experiments during the mid 1980s provided conclusive proof that by repeatedly applying MCPA, dairy farmers had unwittingly been selecting for resistant genotypes thereby creating MCPA-resistant populations of the weed (Bourdôt et al. 1989; Bourdôt et al. 1990; Bourdôt & Hurrell 1991). That this MCPA resistance in giant buttercup has a genetic basis was proven in further experiments (Bourdôt & Hurrell 1991). Furthermore, a simulation modelling study confirmed that giant buttercup populations exposed repeatedly to MCPA in winter or spring (when most farmers spray) can be expected to evolve from being susceptible to being resistant to the herbicide (Leathwick & Bourdôt 1991). Adding to the problem, these MCPA resistant populations are also cross-resistant to MCPB and to 2,4-D (Bourdôt et al. 1994), a predictable outcome given that all three herbicides have the same mode of action (Group O1) (Table 1).

Adding further to problem, once a giant buttercup population has evolved resistance to MCPA, the resistance is effectively permanent. An experiment has shown that 28 consecutive years of discontinued use of MCPA would be required for a resistant population to regress back to being susceptible again (Bourdôt et al. 1996).

The clear message for dairy farmers who do not already have herbicide resistance in their giant buttercup is that they should manage their herbicide use to avoid getting it. One (untested) way of doing this, suggested by the simulation model (Leathwick & Bourdôt 1991), is to apply MCPA after, rather than before, the giant buttercup has flowered. According to the model this allows “susceptible” seeds to be produced and these dilute those from resistant plants. Spraying after flowering also exposes a far smaller fraction of the total population of giant buttercup individuals to the herbicide thereby creating a much lower selection pressure for resistance (Leathwick & Bourdôt 1991). This counter-intuitive idea requires supporting experimental evidence before it could be recommended to farmers.

The other way to reduce the selection pressure for herbicide-resistant genes, and thus avoid, or at least slow the evolution of resistance in a giant buttercup population, is to *rotate between herbicides of different modes of action*. The basic idea is that the less frequently the weed population is exposed to an herbicide of a particular mode of action, the lower the selection pressure for the mutations that confer resistance to that herbicide and other herbicides with the same mode of action. This is the generally accepted practice internationally and is also the practice promoted in New Zealand by the NZ Herbicide Resistance Task Force (NZPPS 2010). There is some potential for this approach with giant buttercup since herbicides that may be applied in pasture either by spraying or wick/wiper and that are known to be effective against giant buttercup, span 7 different mode-of-action groups (B, C3, E, G, 01, 02, 03) (Table 1). This span of mode-of-action groups, within which herbicide rotations could be developed, could, as mentioned in the previous section (4.5), be widened through the use of herbicides in forage crops.

Existing herbicide rotation options
Options for rotating between mode-of-action groups for herbicides with a current NZ label claim for giant buttercup control in pasture that can be sprayed onto pastures are limited to three groups of herbicide – Group B (flumetsulam), Group C3 (bentazone), Group 01 (MCPA) (Table 1). Effectively, this enables only the rotation Flumetsulam / MCPA + bentazone and if applied annually, would be expected to provide little reduction in the rate of evolution of resistance to MCPA or to flumetsulam.

Novel herbicide rotation options
The scope to rotate between different mode-of-action groups can potentially be widened through the use of wiper technologies for herbicide application since this enables additional mode-of-action groups to be added to an herbicide rotation. This scope could, as already mentioned, be widened further through growing forage brassicas and or cereals (such as maize). Field experimentation would be necessary to evaluate wiper applied herbicides and the efficacy of forage crop/herbicide combinations for giant buttercup.

5. ACKNOWLEDGEMENTS

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