Improving the Efficiency of Herbicide Application to Pasture Weeds by Weed-Wiping and Spot-Spraying

A thesis presented in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

in

Plant Science

At Massey University, Palmerston North, New Zealand

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2008

ABSTRACT

This study investigated methods to reduce herbicide application through improved targeting of weeds, thereby also reducing damage to pastures. The focus was to evaluate and improve wiper and spot-spraying application techniques for pasture herbicides as they reduce chemical use by treating just the weed.

Wiper application of herbicides was shown to be a useful technique for controlling Californian thistles. In one trial, a stem reduction of over 90% when assessed 10 months post application was achieved with a double pass of clopyralid, metsulfuron and glyphosate when the plants were treated at the post-flowering stage and were vigorously growing. A double pass was superior to a single pass for glyphosate and triclopyr/picloram, but not for clopyralid and metsulfuron. Subsequent trials produced poor results possibly because of the stressed condition of the thistles and their growth stage as well as lack of consistency in wiper output and operator differences. Despite wiper applicators usually being selective, some damage to pastures was observed in the field, and from a series of experiments it was concluded that rain falling soon after wiper application was the likely cause of pasture damage.

An innovative and highly sensitive technique using a spectrophotometer was developed to measure herbicide output from wiper applicators. A spectrophotometer could accurately measure clopyralid concentrations as low as 0.02 g active ingredient in a litre of water. The Eliminator and Rotowiper outputs were found to be highly variable while the Weedswiper was more consistent although it applied less herbicide than the other two wipers.

Spot spraying experiments confirmed that glyphosate and metsulfuron create bare patches by damaging both grass and clover while clopyralid and triclopyr/picloram only eliminate clover. However, metsulfuron patches stayed bare for much longer while glyphosate ones quickly filled up with weeds and clover. Ingress of clover stolons appeared to be more important than re-establishment from seed in the recovery of patches. The bigger the damaged patch, the higher the likelihood of re-colonisation by opportunistic weeds. Bioassay studies found that over-application of clopyralid and triclopyr/picloram provided residual activity up to 18 and 30 weeks, respectively, thereby potentially preventing re-establishment of white clover. The negative effects on clover seedlings from metsulfuron ranged from 3 to 6 weeks for standard and high rates, respectively, with a stimulatory effect on seedlings thereafter for up to 18 weeks.

Dose-response curves for the application of metsulfuron and triclopyr/picloram into the centre 5% versus full plant coverage of Scotch thistle and ragwort rosettes showed that application of herbicide to the centre 5% was as effective at the same concentration and greatly reduced the risk of damage to pasture.

ACKNOWLEDGEMENTS

My PhD project would not have been possible without technical, financial and moral support provided by so many people but foremost my Chief Supervisor Dr Kerry Harrington and co-supervisors, Professor Peter Kemp and Dr Han Eerens. Dr Kerry Harrington, thank you for letting me take on the study and for your great supervision, motivation, guidance, advice, patience and your passion for the project to succeed. Dr Han Eerens, thank you for your constructive and critical comments on experimental designs and the project in general and for your efficient editing. To Professor Peter Kemp, your critical advice and generosity in sharing knowledge is invaluable. Three supervisors, all different in their approach, one cant wish for more!

Thanks to the Foundation for Research, Science and Technology for their generous funding of this project through the Outsmarting Weeds (# C10X0318) contract, without which this work would not have been possible. Thanks also to the trustees of Helen E. Akers, New Zealand Plant Protection Society, John Hodgson Pastoral Science and Dan Watkins Weed Science Scholarships for your financial support.

Special thanks to my partners in the project, AgResearch, especially Dr Graeme Bourdot, Dr Anis Rahman and Dr Trevor James for their guidance and enthusiasm. I would also like to express my gratitude to John Lucking formerly of Rotoworks for providing the Rotowiper and technical support. Thanks also to Graeme Gates of C-Dax for providing technical information on the Eliminator. Thanks also to John Maddock of Agtronix and Peter Thomson of Agrispray for information on the Weedswiper. Many thanks also to chemical companies for providing some of the herbicides and especially Dr George Mason for sharing your in-depth knowledge of the pesticide industry.

Many thanks go to so many people for their support and help during my study. To Mark Osborne, Tom Dodd and Peter Jessop, I thank you for your help with my field trials. Special thanks to the statistician, Dr Allistair Noble and Dr James Millner for assistance with design and analysis of experiments.

Thanks to Dr David Woolley and Chris Rawlingson for your advice with the spectrophotometer To Lesley Taylor, Steve Ray and all the staff at Plant Growth Unit, thank you for your help with my glasshouse experiments. To Ruth Morrisson and staff at Seed Technology, Craig McGill and Robert Southward, thank you for your assistance with everyday requirements in the Lab. Special thanks to past and current postgrad students at INR for sharing ideas. Thanks also to France Prevost for help in formatting the document.

Many thanks to my friends, cousins, my brothers and sisters for making me feel proud of my work. My parents, for instilling the value of education in me, I will forever be grateful. To my wife, Maciline, thanks for your love, support and encouragement. Finally, to my daughter Rayirai, my son Tafara and niece Tafadzwa, thanks for bringing back the smile when times were tough.

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1 Introduction, objectives and thesis structure

1.1 Introduction

Herbicides constitute 66% of pesticides used in New Zealand, with the pastoral sector accounting for more than 55% of the total herbicides used (Walker et al., 2004). More than half of the herbicides used are phenoxy herbicides for control of broad-leaved weeds in pastures (Holland & Rahman, 1999). The phenoxyacetic herbicides (2,4-D and MCPA) cause damage to clovers while the phenoxybutyrics do not but the latter are less effective against mature weeds (Meeklah, 1958; Fitzgerald, 1959; Thompson, 1974; Honore et al., 1980). The more effective synthetic herbicides such as clopyralid, picloram, and dicamba are also much more damaging to clovers (Newton, 1965; Thompson, 1974).

In New Zealand nodding thistle (*Carduus nutans* L.), slender winged thistle (*Carduus pycnocephalus* L.) (Harrington et al., 1988; Harrington, 1989), and giant buttercup (*Ranunculus acris* L.) (Bourdot et al., 1990) have evolved resistance to phenoxy herbicides due to high selection pressures because of repeated use of these herbicides.

There are also concerns for the risk of damage that phenoxy herbicides cause to desirable non-target plants as a result of spray drift (Thompson, 1965, O'Connor, 2004). Small quantities of herbicides (mostly triazines) and other herbicides normally used in pastures such as (2,4-D, MCPA, dicamba and picloram) have been detected in groundwater and this has heightened public concerns on pesticide use (Close & Rosen, 2001). Although herbicide residues detected in water are generally at extremely low concentrations, the fact that they are detected at all is a cause for concern to the public in general.

Herbicide application with boom sprayers, spray guns or knapsack sprayers is often not very precise, with significant amounts of chemical hitting the pasture around the weed due to over-application. Research has shown that only a fraction of the total herbicide applied (<5%) is usually required to control weeds in cereals with the rest hitting the crop and soil (Combellack, 1981; Pimentel, 1995). Thus, often more than 95% of herbicides used may simply contaminate the environment.

Because of the problems associated with overuse of herbicides and imprecise application techniques, there is now a growing trend towards reducing pesticide use, necessitating research in application methods that are more efficient. Research focused on improving application efficiency is seen as important from the perspective of protecting desirable plant species as well as reducing pesticide loading in the environment (Smith & Thomson, 2003).

Combellack (1989) has identified strategies by which herbicide use efficiency can be improved including timing of application, targeting herbicides to weeds, use of effective formulations and adjuvants and raised threshold levels. He estimated herbicide savings of up to 75% by spraying weeds only where they occur. Other researchers have developed concepts such as “minimum lethal herbicide dosage” to reduce herbicide use (Kempenaar et al., 2002). Since most non-herbicide options (although they have a place in the overall weed management systems) are known to be less effective especially in cereals, grass and root crops (Wookey, 1985), the more efficient application of herbicides has become a priority in weed science research (Combellack, 1989).

Current herbicide application methods for weed control in pastures are commonly to spray herbicides evenly throughout the field. However, weeds are not necessarily evenly distributed across the field, but often grow in patches with most of the field being weed-free (Christoffoleti & Shiratsuchi, 2001). Herbicides could be saved by not treating the weed-free areas of the field (Ramon et al., 2002).

Spot herbicide treatments are applied when weeds are confined to small areas at low densities, which in New Zealand is commonly done using a spray gun or a knapsack sprayer (Matthews et al., 2000). For spot application, some more effective herbicides such as picloram, triclopyr, and dicamba are either applied by themselves or added to the phenoxy herbicides to improve the efficacy and spectrum of weed control (Martin et al., 1988). The practice of spot-spraying weeds to run-off means that pasture plants beside the weeds may also receive a lethal herbicide dose. The bare ground resulting from the demise of the target weed plant and non target pasture plants is likely to be colonised by opportunistic weeds of low forage value (McConnaughay & Bazzaz, 1987).

Despite spot spraying having been practised for many years in New Zealand, limited effort has gone into quantifying the damage caused to surrounding pasture and estimating the time it takes for the damaged patches to recover. Nor are there published data on the effects of applying these translocated herbicides only to the centre of weeds instead of full plant coverage as a technique to minimise damage without affecting herbicide performance.

Improved herbicide application techniques in pastures can lead to improved herbicide efficiency and reduced environmental contamination, while allowing use of more effective herbicides thereby reducing some of the adverse effects of herbicides. This can be done by targeted application of herbicides by using weed wipers and improving the efficiency of the spot spraying technique. It could also play a major role in preventing the development of herbicide resistance by allowing use of more herbicide groups.

For some weed species that are difficult to kill, farmers need to apply herbicides that generally are very damaging to pasture (e.g. glyphosate) and these have to be applied with high precision on target plants to minimise pasture damage (Matthews et al., 2000). Herbicide wipers allow accurate placement of herbicides onto tall and erect weeds that stand out above pasture, such as Californian thistles (*Cirsium arvense* (L.) Scop.)), rushes (*Juncus* spp.) and ragwort (*Senecio jacobaea* L.) (Dale,1978; Wills & McWhorter, 1981; Thompson, 1983; Martin et al., 1990; Toor, 1994).

Although wiper applicators have been in use in New Zealand for some time, much remains to be learned about this technology. There is little information on the relative performance of different wiper applicators and how their design influences weed control. There is also limited published data on effectiveness of weed wipers for controlling Californian thistle at different stages of growth in pastures using different herbicides and how these herbicides affect pasture. Where these data exist, the results from many authors are too variable to make many useful conclusions on the use of weed wipers in pastures (Thompson, 1983; Meeklah & Mitchell, 1984).

1.2 Objectives

Because of the problems caused by overuse of phenoxy herbicides and poor application techniques, the general aim of this study was to find ways of reducing the amount of herbicide used within pastures by targeting herbicides only to the weeds. This will greatly reduce the quantity of herbicide being used in New Zealand pastures, and should help overcome some of the resistance and environmental problems currently being experienced.

The specific objectives of this study were:

- to investigate techniques for selectively applying herbicides on weeds growing in pasture with minimum damage to desirable species.
- to quantify the impact of spot-spraying treatments on pasture plants around weeds that get exposed to herbicides.
- to increase the precision and efficiency of spot-spraying herbicides to target weeds by application to the centre of weeds only.
- to investigate how selectively wiped herbicide is sometimes transferred to pasture causing damage.
- to develop a technique for accurately measuring how much herbicide is applied to weeds by wiping equipment, thus ffacilitating research into factors affecting wiper application of herbicides.

1.3 Thesis structure

This thesis consists of eight chapters. This introductory chapter (Chapter 1) has explained why this research was undertaken.

Chapter 2 is a literature review that provides some detail on the herbicides used in pastures, application techniques used with pasture herbicides, and outlines history of the development of wiper applicators. Chapter 3 investigates the impact of spot-spraying treatments on pasture plants around weeds that get exposed to herbicides. Chapter 4 also deals with spot-application of herbicides by investigating the effect of applying translocated herbicides only to the centre of plants instead of full coverage. A poster paper has been published based on the results from Chapter 4 (Moyo et al., 2007).

The remainder of the thesis deals with use of wipers to target pasture weeds with herbicides. Chapter 5 investigates the effectiveness of wiper application of herbicides to Californian thistles. A poster paper has also been published based on this chapter (Moyo et al., 2006).

Chapter 6 follows up on the previous chapter in which explanations are sought for why pasture damage can occur after wiper application of herbicides to weeds. Chapter 7 describes a technique to measure the amount of herbicide deposited on weeds by wipers, and it is used to investigate several factors affecting the quantity of herbicide applied by wipers. Chapter 8 summarises the main findings and discusses these results in relation to the objectives of this thesis.

1.4 References

Bourdot GW, Hurrell GA & Saville DJ (1990) MCPA-resistance in giant buttercup (*Ranunculus acris* L.) in North Island dairy pastures. In: *Proceedings 1990 New Zealand Weed and Pest Control Conference,* Dunedin, New Zealand, 233-236.

Christoffoleti PJ & Shiratsuchi LS (2001) The potential of patch weed control in Brazil. In: *Proceedings 2001 British Crop Protection Conference: Weeds*, Brighton, UK, 835-840.

Close ME & Rosen MR (2001) 1998/99 National survey of pesticides in groundwater using GCMS and ELISA. *New Zealand Journal of Marine and Freshwater Research* **35**, 205-219.

Combellack JH (1989) Resource allocations for future weed control activities. In: *Proceedings 1989 New Zealand Weed and Pest Control Conference*, New Plymouth, New Zealand, 15-30.

Fitzgerald JN (1959) A review on the use of Phenoxybutyrics in New Zealand. In: *Proceedings 1959 New Zealand Weed Control Conference,* Tauranga, New Zealand, 49-53.

Harrington KC (1989) Distribution and cross-tolerance of MCPA-tolerant nodding thistle. In: *Proceedings 1989 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 39-42.

Harrington KC, Popay AI, Robertson AG & McPherson HG (1988) Resistance of nodding thistle to MCPA in Hawkes Bay. In: *Proceedings 1988 New Zealand Weed and Pest Control Conference,* Auckland, New Zealand, 219-222.

Holland PT & Rahman A (1999) Review of trends in agricultural pesticides use in New Zealand (ed. Ministry of Agriculture and Forestry), 53.

Honore EN, Rahman A & Dyson CB (1980) Effects of winter application of phenoxy herbicides on white clover and pasture production in lower Northland. In: *Proceedings 1980 New Zealand Weed and Pest Control Conference,* Tauranga, New Zealand, 55-58.

Kempenaar C, Groeneveld RM, Uffing AJ & Weide R (2002) New insights and developments in the MLHD-concept of weed control. In:

Proceedings 2002 European Weed Research Society Symposium, 98-99.

McConnaughay KDM & Bazzaz FA (1987) The relationship between gap size and performance of several colonizing annuals. *Ecology* **68**, 411-416.

Martin P, Thompson A & Rahman A (1988) Spot treatment of ragwort and nodding thistle with DPX-L5300. In: *Proceedings New Zealand Weed and Pest Control Conference,* Auckland, New Zealand, 223-225.

Matthews PNP, Harrington KC & Hampton JG (2000) Management of grazing systems. In: *New Zealand pasture and crop science* (eds J White & J Hodgson), 153-174. Oxford University Press, Melbourne.

Meeklah FA (1958) Comparison of the substituted phenoxyacetics and phenoxybutyrics on a white clover - perennial ryegrass sward. In: *Proceedings 1958 New Zealand Weed Control Conference*, Blenheim, New Zealand, 61-67.

Meeklah FA & Mitchell RB (1984) Evaluation of herbicides for control of Californian thistle. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 20-23.

MOYO C, HARRINGTON KC, KEMP PD AND EERENS, JPJ (2006). Wiper application of herbicides to Californian thistles. In: *Proceedings 2006 New Zealand Plant Protection Society*, Blenheim, New Zealand, 361.

MOYO C, HARRINGTON KC, KEMP PD AND EERENS, JPJ (2007). Effectiveness of spraying herbicides on the centre compared to the whole plant of Scotch thistle (*Cirsium vulgare*) rosettes. In: *Proceedings 2007 New Zealand Plant Protection Society*, Napier, New Zealand, 321.

Newton IS (1965) The effect of picloram on clover. In: *Proceedings 1965 New Zealand Weed Control Conference*, Hamilton, New Zealand, 42-46.

O'Connor B (2004) Novachem Manual 2004/2005. In: *Novachem Manual* (Novachem Services Limited), Palmerston North 488 pp.

RAMON H, ANTHONIS J, VRINDTS E et al. (2002) Development of a weed activated spraying machine for targeted application of herbicides. *Aspects of Applied Biology*, 147-164.

SMITH LA & THOMSON SJ (2003) United States Department of Agriculture-Agricultural Research Service research in application technology for pest management. *Pest Management Science* **59**, 699-707.

THOMPSON A (1974) Herbicide effects on ragwort and pasture. In: *Proceedings 1974 New Zealand Weed and Pest Control Conference,* Nelson, New Zealand, 90-93.

THOMPSON A (1983) Pasture weed control by rope wick applicator. In: *Proceedings 1983 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 96-98.

THOMPSON FB (1965) Misuse of Pesticides. In: *Proceedings 1965 New Zealand Weed and Pest Control Conference*, Hamilton, New Zealand, 129-132.

WALKER J, MANKTELOW D, GURNSEY S et al. (2004) Trends in pesticide use in New Zealand (ed. Ministry for the Environment).

WOOKEY CB (1985) Weed control practice on an organic farm. In: *Proceedings 1985 British Crop Protection Conference, Weeds,* 577-582.

Chapter 2

2 Literature Review

2.1 Introduction

Several definitions of a weed have been proposed. The Weed Science Society of America defined a weed as a plant growing where it is not wanted (Buchholtz, 1967). This definition has been widely adopted (Anderson, 1996). The European Weed Research Society defined a weed as any plant or vegetation, excluding fungi, interfering with the objectives or requirements of people (Mortimer, 1990). Weeds have also been defined in ecological terms. For example, Aldrich & Kremer (1997) defined a weed as a plant that originated under a natural environment and, in response to imposed and natural environments, evolved and continues to do so as an interfering associate with our desired plants and activities. This definition incorporates the dynamic nature of weeds in time and space.

Weeds are part of every land based production system and need to be managed appropriately to reduce their economic impacts (Eerens et al., 2002a). Weeds in pastures are not always obvious since most of the plants that are called ‘weeds’ have some forage value and improve the productivity of pastures at some stage (Harrington et al., 2006). Consequently, most of these plants will therefore only become weeds when they reach a density that reduces livestock health and productivity or are too competitive for the desired and deliberately sown species (Smith & Martin, 1995). Management decisions to control weeds will therefore take into account the type of weed present, their density and their stage of development.

New Zealand pastoral agriculture relies heavily on perennial ryegrass/white clover pastures to provide livestock feed (Kemp et al., 2000). Perennial ryegrass (*Lolium perenne* L.) is the most commonly used grass species in permanent pastures and white clover (*Trifolium repens* L.) is the most common legume component (Kemp et al., 2000; Seefeldt et al., 2005). The grasses and legumes in pastures present a challenge in as far as herbicide use is concerned since most herbicides are either selective to grasses or legumes (Bourdot et al., 2007). Boom spraying herbicides such as MCPA and 2,4-D causes an undesired suppression of clovers and necessitates the use of other application methods to complement broadcast application.

The objectives of this literature review were to provide a background to the problems caused by weeds in pastures as well as the current control options. The challenges of selective control of weeds in a mixed ryegrass/legume pasture are also reviewed. The overuse of phenoxy herbicides and their effects will be discussed. The modes of action of more effective alternative herbicides in pastures are discussed, as are means by which these herbicides could be applied more efficiently to reduce pasture damage by applying them only to weeds. This review will also evaluate the performance of herbicide wipers in the selective placement of translocated herbicides to weeds growing in pastures in order to assess the current level of understanding in the use of weed wipers.

2.2 Problems caused by pasture weeds

There are currently 187 plant species classified as weeds in New Zealand pastoral agriculture costing farmers NZ$1.2 billion annually (Bourdot et al., 2007). Pasture weeds can be classified according to their impact on the productivity of the sward.

2.2.1 Competition

Weeds are undesirable since they compete with pasture grasses and legumes for the same resources such as light, water, and mineral nutrients (Ross & Lembi, 1999; Grice & Campbell, 2000). Competition between two or more species occurs when the combined demand for a factor such as nutrients is greater than the immediate supply of that factor (Aldrich & Kremer, 1997). Therefore, pasture grasses and legumes also exert an important effect upon the weed and this can be used in managing weed competition. For example, maintaining a dense and vigorous sward especially in late summer and autumn reduces the effect of weeds from competition (Popay & Thompson, 1980; Bourdot, 1996; Eerens et al.; 2002b). Preferential grazing of sown pasture species coupled with avoidance of unpalatable and poisonous ones reduces the competition faced by invading weeds, allowing them to dominate.

2.2.2 Avoidance and reduced utilisation

The main problem caused by weeds in pastures is the prevention of livestock from accessing the pasture immediately surrounding the weed (Hartley & James, 1979; Smith & Martin, 1995). Thistles with their prickly leaves are generally avoided as are poisonous plants such as hemlock (*Conium maculatum* L.) and ragwort (S*enecio jacobaea* L.). An experiment to assess the cost benefit of selective control of Californian thistles (*Cirsium arvense* L.) in Waikato found that this species affected pasture production indirectly through impaired pasture utilisation (which in turn affected animal production) rather than by direct competition (Hartley & James, 1979). Californian thistle affected sheep more than cattle. This rejection of certain less preferred species of weeds by livestock can actually promote their dominance in pastures unless a reasonable grazing pressure is maintained (Matthews et al., 2000). Scrub weeds such as gorse (*Ulex europaeus* L.), broom (C*ystis scoparius* L.), and bracken (*Pteridium esculentum* L.) make it difficult for stock to graze some standing forage thereby reducing *utilisation*.

Some weedy plants such as docks (*Rumex* spp.) and rushes (*Juncus* spp.) are unpalatable or are of low nutritive value as compared to the desirable pasture species, thus taking space that could have been used to grow more nutritious species (Dowling et al., 2000). An experiment carried out to estimate the economic loss sustained due to the dominance of giant buttercup (*Ranunculus acris* L.) in dairy pastures in New Zealand, estimated the national economic loss due to this weed to be NZ $118 million in the 1999-2000 year (Bourdot & Saville, 2002).

2.2.3 Plants that affect product quality

Weeds can reduce the quality and value of livestock products. For example, seed heads from barley grass (*Critesion* spp.), and thistles contaminate wool reducing its value (Smith & Martin, 1995; Dowling et al., 2000).

Weed species with a high aromatic content can taint milk or meat flavour of the stock that eat them e.g. stinking mayweed (*Anthemis cotula* L.), twin cress (*Coronopus didymus* L.), (Matthews et al., 2000), Capeweed (*Arctotheca calendula* L. (Levyns)), (Dowling et al., 2000), and wild onion (*Allium vineale* L.) (Williams, 1984).

2.2.4 Plants that affect livestock health

Some weeds in pastures can cause acute or chronic poisoning when consumed by livestock as they contain toxic compounds that can injure or kill animals even in small doses. Ragwort contains a number of poisonous alkaloids that can poison cattle, although sheep and goats are less susceptible to these toxins. Other species such as hemlock also contain toxic alkaloids that can cause birth defects in pregnant animals or even death. Some weeds such as thistles, barley grass, nassella tussock (*Nassella trichotoma* Nees (Hack.), and wiregrass (*Aristida* spp.) cause physical injury to livestock leading to an increase in scabby mouth due to secondary viral infections through punctures in the mouth (Smith & Martin, 1995; Dowling et al., 2000).

Plants like barley grass are referred to as “transitional weeds” since they provide good quality forage in their vegetative stages. However in the mature stages the nutritive value decreases and the seed heads produced are damaging to animal skins (Dowling et al., 2000). However, some weeds, because of their mineral composition, have beneficial medicinal properties that when grown in small numbers actually benefit productivity (Harrington et al., 2006).

2.2.5 Allelopathic plants

Some weeds are thought to be allelopathic and release chemicals into the environment that can reduce the production of desirable pasture plants in their surroundings (Stachon & Zimdahl, 1980; Smith, 1990). Research by Ahmed & Wardle (1994) found that ragwort may have an allelopathic influence on perennial ryegrass (*Lolium perenne* L.) and pasture legumes with the legumes being more susceptible. Wardle et al. (1993) also found that nodding thistle (*Carduus nutans* L.) had an apparent allelopathic effect on six grass species and four legume species and that the weed was most allelopathic at the rosette stage. Some weeds e.g. stinking mayweed have been found to have allelopathic influences on lucerne (*Medicago sativa* L.) cv. Saranac and Italian ryegrass (*Lolium multiflorum* (Lam)) seedlings (Smith, 1990). Other plants known to have some allelopathic potential include Californian thistle, chickweed (*Stellaria media* L. (Vill)), purple nutsedge (C*yperus rotundus* (L.)), yellow nutsedge (C*yperus esculentus* (L.)), and couch grass (*Elytrigia repens* L. (Beauv)) (Smith & Martin, 1995).

The importance of allelopathy is not well documented since it is difficult to separate its effects from that of competition for nutrients and water (Ross & Lembi, 1999). Proof of its effects would require steps that involve isolation of the suspected allelo-chemical as well as monitoring its release, movement and uptake in the natural environment to see if quantities produced are sufficient to cause the observed effect (Aldrich & Kremer, 1997).

2.3 Economics of herbicidal weed control in pastures

The decision to spray with a herbicide is a complex one, depending on the objectives of the farmer. Jones (2000) argues that the objective of any control programme would be to maximise profit rather than yield and the decision to spray should be based on that. The economic threshold level can be used to compare the benefits and costs of weed control when deciding whether to spray.

2.3.1 Economic threshold level

The Economic Threshold Level (ETL) is the weed density at which the cost of control equals the financial benefit derived from controlling the weeds in that same year (Cousens et al., 1985). When the weed density exceeds the threshold level, the cost of herbicide application is less than the financial losses as a result of reduced production.

Moore et al. (1989) constructed a mathematical model of nodding thistle reproduction, growth and competition with grass to measure the long-term economic implications of controlling infestations on grazed pasture in New Zealand using the herbicide MCPB. The study found that it was beneficial in the long term to apply the herbicide in October or whenever nodding thistle ground cover exceeded 2.5%. This work confirmed that timing and weed density are important considerations in constructing an economic threshold level.

The cost of control and expected financial gain are important factors in any decision to spray. In a survey conducted by Toor & Stuck (1993), New Zealand farmers were found to base their decision to control weeds and pests on the cost of control and the availability of surplus funds. Since most herbicides cause some damage to pasture, any decision to spray must also take that productivity loss into account. The cost of control has to be related to the expected benefits as illustrated in an experiment by Hartley & Atkinson, (1978). They found that the cost of controlling barley grass was $13-31/ha and benefits ranged from $52 to $74/ha due to increased lamb production. Price volatility of the product and herbicide will cause shifts to the economic threshold.

Economic threshold levels are not widely used by farmers because of various limitations (Cousens, 1987; Pannell, 1987). One problem with economic thresholds is that the competitive ability of pastures varies depending on soil fertility, moisture stress and other environmental factors. The occurrence of weed species in combinations with each other at different ratios makes the concept of ETLs difficult to implement in pastures. It follows therefore that a particular weed/crop/environment combination is likely to have a number of thresholds (Pannell, 1987).

Another problem with the use of thresholds in pastures is in measuring the economic benefits of controlling weeds in pastures. For the thresholds to make sense, any increase in herbage production as a result of herbicide treatment has to be utilised by the livestock before financial benefits can be realised (Haggar et al., 1990).

Although the main reason to control weeds in pastures might be economic, some farmers do so for aesthetic reasons (Haggar et al., 1990). A tidier looking farm gives an impression of good management. However, controlling weeds just to keep the farm tidy carries both direct costs (chemical costs and application) and indirect opportunity costs (Haggar et al., 1990).

Besides an economic yield loss in the current season, other concerns may determine when weed control is justified. For example, weed densities might not be economic to control in one year but failure to take action might lead to more adverse economic problems due to weeds building up through seed production. The large numbers of seeds that can be produced by a single plant requires the threshold concept to be extended to include potential future impacts of the current weed population. Farmers who therefore apply herbicides to low densities of weeds to prevent seed build up are trying to maximise the benefits of weed control over a long time frame as compared to those who want to maximise benefits in a single year. Many farmers in New Zealand use an annual winter application of 2,4-D to their paddocks because it is cheap and it is an insurance that stops small thistles and docks from becoming serious problems in future. The winter application of herbicides is considered less damaging to clover. Dairy farmers usually apply low rates of nitrogen to stimulate early grass growth. These factors, combined with the increased incidence of clover root weevil make clover damage from herbicides of relatively low concern.

Most economic thresholds have been criticised for failing to take into account the carryover effects of weeds and herbicide use from year to year (Cousens, 1987). An experiment carried out by Popay et al. (1989) found that annual applications of MCPA at 1 kg/ha in the control of giant buttercup were more profitable than less frequent applications because of the large benefits and relatively small control costs, even when clover damage was taken into account. Although MCPB did not damage clover, it was less profitable than MCPA because it was less effective in weed control. However, a shift towards more winter active clover cultivars is now raising questions about this calendar spraying which is based on the assumption of winter dormant clover.

Environmental considerations and public concerns about the use of agrochemicals mean that some farmers tolerate higher levels of weed infestation before a decision to spray is reached (Cousens, 1987). This introduces yet another factor to the concept of economic threshold levels.

2.4 Chemical weed control

Herbicides are an important tool in controlling weeds in pastures, but many herbicides severely retard or remove clover from the sward, and some also suppress pasture grasses (Edmonds et al., 1982; James et al., 1999). The method, rate and timing of herbicide application have an important bearing on the impacts of a weed control programme.

2.4.1 Herbicide application

The aim of herbicide application should be to apply the minimum effective dose at the right time with minimum risk to both the operator and environment (Combellack, 1981). The herbicide and application rates are extremely important in chemical weed control. High rates increase the risk of pasture damage while rates that are too low will not give adequate weed control. The Minimum Lethal Herbicide Dosage (MLHD) technique developed for use in cereals in the Netherlands is a method that ensures that only the required amount of herbicide is applied to the weeds (Kempenaar et al., 2002). However, herbicide rates lower than the label recommendations as is mostly the case with the MLHD technique, are known to give variable results (Doyle & Stypa, 2004).

Some herbicides are applied by ground or aerial boom sprayers, resulting in broadcast applications that cover the entire area. Broadcast application of the herbicide is done if the weeds are widely dispersed throughout the sward

(Williams, 1984). The most common herbicides used for boom spraying in pasture swards are the phenoxy herbicides, MCPA and 2,4-D (Matthews et al., 2000).

Spot herbicide treatments are applied when weeds are confined to small areas at low densities, which in New Zealand is commonly done using a spray gun. For spot application, some more effective herbicides such as picloram, triclopyr, and dicamba are either applied by themselves or added to the phenoxy herbicides to improve the efficacy and spectrum of weed control. Herbicide application (especially boom-spraying and to some extent spot treatment) is often not efficient with significant amounts sometimes being lost to the environment, causing pollution and damage to non-target organisms (Swarbick, 1981). Mature weeds are more likely to survive boom-spraying using phenoxy herbicides (Taylor, 1973; Martin et al., 1988) and thus would require spot treatment using more potent (and more damaging to clover) herbicides such as picloram and dicamba mixed with the phenoxys. However, picloram is more persistent in the soil hindering clover recovery.

For some weed species which are difficult to kill, farmers need to apply herbicides that generally are very damaging to pasture and these herbicides have to be applied with high precision on target plants to minimise pasture damage (James et al., 1997). Herbicide wipers allow accurate placement of herbicides onto tall and erect weeds that stand out above pasture, such as Californian thistles, rushes and ragwort. Summer is generally the period when flowering ragwort and several other thistles stand out above the pasture, making it the most suitable time for weed-wiping.

2.4.2 Timing of application

Timing of herbicide application is crucial to a successful weed control programme. The susceptibility of weeds to herbicides depends on the age and health of the plant as well as environmental conditions. Applications should be done when weeds are at their most susceptible developmental stage and weather conditions are favourable. Generally, younger plants are easier to kill than older stages (Wardle, 1987). Certain development stages are also more susceptible than others. Harrington & Ivens (1983) have found that applying glyphosate to Californian thistle at the post-flowering stage within a pot experiment was more effective than at any other stage. In autumn, most photo-assimilates move to the roots for storage (Wilson & Michiels, 2003). It is therefore assumed that application of translocating herbicides in autumn will lead to sufficient amounts being translocated to the root where they exert a toxic effect.

2.4.3 Herbicides used in New Zealand pastures

Several herbicides are used in New Zealand pastures. These herbicides are applied in a number of ways including boom spraying, spot treatment and weed wiping. The most commonly used herbicides are described below.

2.4.3.1 Phenoxy herbicides

The phenoxys have a common structure that includes a phenyl (benzene) ring attached to an oxygen atom which is in turn attached to an acid, and various substituents on the ring (Anderson, 1996). These substituents give the different herbicides in this group their distinct properties. The chemical structure of phenoxys resembles that of the naturally occurring plant growth regulator auxin, and thus they are also known as hormone herbicides.

The phenoxy herbicides are weak acids that are only slightly soluble in water and oils. Although the acid is the active form, the phenoxy herbicides are normally formulated as water soluble amines or oil soluble esters for ease in handling and application (CAST, 1975; Anderson, 1996). The strength of commercial formulation is expressed in terms of the equivalent content of the parent acid (CAST, 1975). Applied in their salt or ester form, the phenoxy herbicides are converted within the plant to their respective acid forms, and it is this form that is ultimately toxic to plants.

Esters of phenoxy herbicides are formed by the reaction of their acid form with an alcohol. The resulting ester molecule is non-ionic, does not dissociate in water and thus does not react with calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in hard water to form precipitates. The alcohol used determines the type of ester for the phenoxy herbicide formed e.g. methyl and ethyl esters are formed when methanol and ethanol, respectively, are reacted with the parent acid. These short chain esters are highly volatile under ordinary temperatures (Bovey, 1995). This volatility can be reduced by use of low–volatile (long chain) esters which generally cost more than high volatile esters and are less effective as herbicides in some situations (CAST, 1975). Low-volatile esters are formed when two or more alcohols react with a parent acid to form long-chain esters. Esters of the phenoxy herbicides are soluble in oils and insoluble in water and are thus commonly formulated as emulsifiable concentrates for application in either water or oil carriers.

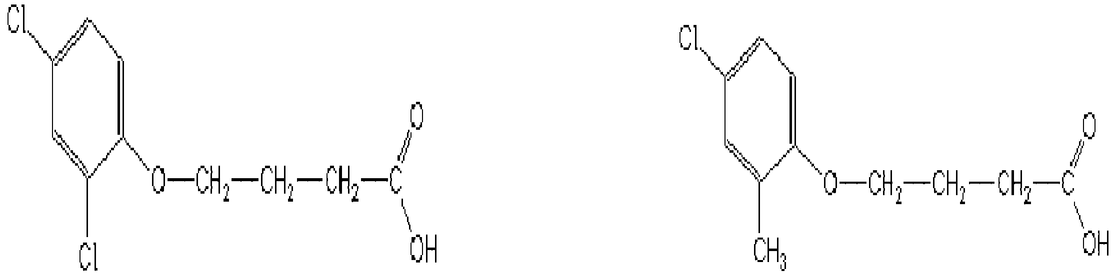
The parent acid of phenoxy herbicides can react with bases to form salts. Common salt formulations include sodium, potassium, ammonium and several other amine salts (Kearney & Kaufman, 1975a). The salt formulations dissolve and ionise readily in water forming true solutions. The amine salts are generally the most soluble in water and therefore, the most common salt formulation. In hard water the Ca^{2+} and Mg^{2+} ions may form insoluble precipitates with anionic portions of these herbicides reducing the amount and effectiveness. These precipitates may clog filters and nozzles (CAST, 1975). The amine salts are less affected by hard water than sodium and ammonium salts. Unlike ester formulations, salts of phenoxy herbicides are non-volatile.

Ester formulations are generally considered to be more toxic to plants than salt formulations. Klingman & Ashton (1982) proposed that the volatility of esters may permit absorption of the gases through the stomata; the wetting action of the oil-like ester and the oil carrier may actually aid penetration of the stomata and that the low polarity of ester forms are more compatible with the cuticle and aid penetration directly through the cuticle.

Frequent use of phenoxy herbicides has led to biotypes of nodding and slender winged thistles (*Carduus pycnocephalus* L.) that are resistant to this group of herbicides (Harrington, 1989). Biotypes of giant buttercup have also become resistant to MCPA (Leathwick & Bourdot, 1991). Therefore farmers should adopt management strategies that minimise the resistance of weeds to phenoxy herbicides. Other herbicides with a different mode of action and target site such as metsulfuron and glyphosate can be applied in pastures using weed wipers. The addition of other herbicides to phenoxys such as clopyralid will reduce the chances of weeds developing resistance (Harrington, 1996) while the use of weed wipers ensures selective application of the herbicides to reduce damage to pasture. The two groups of phenoxy herbicides, the phenoxybutyrics and phenoxyacetics are described below.

2.4.3.1 MCPB and 2,4-DB

MCPB and 2,4-DB (Fig 2.1) belong to phenoxybutyric group of herbicides. These herbicides translocate within the plant and accumulate at the meristems of roots and shoots where they interfere with nucleic acid metabolism (Anderson, 1996). The two herbicides both control the seedlings of many broad-leaved weeds including docks and Californian thistles but are generally ineffective against more mature weeds.



(a) 2,4-DB

(b) MCPB

Fig 2.1 The structure of 2,4-DB (a) and MCPB (b)

The greatest benefit of the two herbicides is that they do not cause any damage to either pasture grasses or clovers. Pasture legumes do not have the necessary enzyme that converts 2,4-DB and MCPB from their non-toxic forms to the toxic molecules of 2,4-D and MCPA respectively, hence are generally tolerant to these herbicides (Matthews et al., 2000). Although MCPB and 2,4-DB are safe on ryegrass and clovers they are not used as extensively as other phenoxy herbicides such as MCPA and 2,4-D because of their relatively higher cost (Williams, 1984) and low efficacy against mature weeds.

2.4.3.2 MCPA and 2,4-D

MCPA and 2,4 D (Fig 2.2) are referred to as phenoxyacetic herbicides and are the active forms of MCPB and 2,4-DB respectively.

(a) MCPA (b) 2,4-D

Fig 2.2 The structure of (a) MCPA and (b) 2,4-D

MCPA and 2,4-D are selectively toxic to most broad-leaved plants (including suppression of clover) without harming grasses. These two herbicides are the most commonly used herbicides in New Zealand pastures for boom-spraying because they are more effective against more mature weeds (Matthews et al., 2000) and cheaper compared to suitable alternatives such as MCPB and 2,4-DB. An experiment by Taylor (1973b) to investigate the effectiveness of phenoxy herbicides on ragwort plants found that 2,4-D amine at 1.0 kg/ha killed all ragwort plants compared to 90 % killed using 2,4-DB at 2.0 kg/ha.

Although MCPA and 2,4-D are chemically very similar, their effectiveness against certain species differs. Trials in New Zealand have shown that 2,4-D is superior to MCPA in the control of ragwort though MCPA is more effective against thistles than 2,4-D (Thompson & Saunders, 1984). However, farmers usually prefer to use 2,4-D even in situations where MCPA could be the better herbicide since the former is cheaper (Popay & Thompson, 1983).

The main weakness of MCPA and 2,4-D is that they cause clover suppression and are not as effective as other herbicides like picloram, dicamba and clopyralid in controlling very mature weeds as well as perennials. An experiment by Hartley (1983) in Palmerston North (NZ) to study the effect of

MCPA on sheep live weight gain, when controlling Scotch thistles (*Cirsium vulgare* (Savi) Ten) found that the damage caused by the herbicide was equivalent to the damage caused by 1.67 thistle plants /m^2. MCPB did not cause any reduction in the live weight of the sheep. Thus, it would appear not worthwhile to control thistles with MCPA at a lower weed density given the level of damage to clover.

In New Zealand, MCPA is available as a potassium salt formulation while 2,4-D is available as both an ethylhexyl ester and a dimethylamine salt formulation (O'Connor, 2004) with the former being more effective for weed control. MCPA and 2,4-D have short soil residual lives of up to 6 and 4 weeks respectively. This is an important consideration for clover recovery (CAST, 1975).

2.4.3.2 Dicamba

Dicamba is a substituted benzoic acid herbicide with a characteristic benzene ring attached to a carboxylic acid group (Anderson, 1996). The chemical structure of dicamba is shown in Fig 2.3.

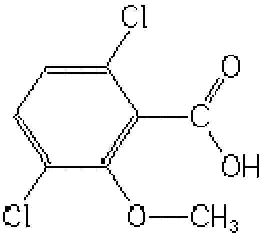


Fig 2.3 The structure of dicamba

Benzoics move from leaves to the terminal meristems of leaf, shoot, and root, and can also move in the transpiration stream. In some cases, benzoic herbicides applied to plant foliage may come in contact with the soil and then be absorbed by plant roots as well. Dicamba remains active in the soil for up to two months depending on climate, soil conditions and rate used, making re-establishment of clovers difficult (Rahman et al., 1981).

Dicamba produces auxin-like (growth hormone) symptoms which result in excessive cellular growth. Monocotyledons are more tolerant of dicamba due to rapid metabolism. Chang & Vandern Born (1971) found that the metabolism of the herbicide within the plant occurred very slowly in susceptible weeds such as Californian thistles and rapidly in tolerant crops such as wheat (*Triticum aestivum* L.).

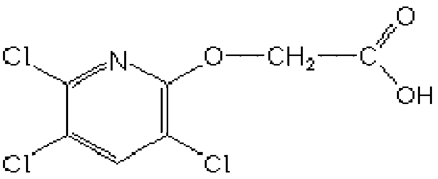
Dicamba is rarely used on its own but is mixed with other herbicides to increase its efficacy and spectrum of weed control (Kearney & Kaufman, 1975b). The mixtures commonly include the phenoxy herbicides 2,4-D and MCPA. The ability of dicamba to translocate well within plants makes it a good choice for application by weed wipers to minimise damage to pasture (Chang & Vandern Born, 1971; Tomlin, 2000).

2.4.3.3 Clopyralid, picloram and triclopyr

Clopyralid, picloram and triclopyr are growth regulator-type pyridine herbicides. Their chemical structure has the pyridine ring in common (Fig 2.4). The ring is similar to that of benzene with a nitrogen atom replacing a carbon atom in the ring (Anderson, 1996). The three herbicides are readily absorbed by foliage and roots, and translocated within the plant to the growing points where they interfere with cell growth (Tomlin, 2000).

(a) Clopyralid

(b) Picloram



(c) Triclopyr

Fig 2.4 The structure of clopyralid (a), picloram (b), and triclopyr(c)

Unlike the phenoxys, pyridine herbicides have significant soil activity. Depending on soil type and environmental conditions, picloram may have soil activity for 2-3 years or even longer while clopyralid and triclopyr remain active in the soil for 2-4 months (Kearney & Kaufman, 1975b). Pyridine herbicides are water-soluble and generally not strongly adsorbed to soil, and therefore susceptible to leaching. Action is similar to phenoxy herbicides but more effective on many broadleaf weed species. Pyridine herbicides are metabolised by grasses and certain broadleaf weeds which serves as the major mechanism of plant selectivity (Zimdahl, 1999). However, their main problem is that they cause complete clover death at standard application rates.

The three herbicides are commonly used in mixtures for spot spraying to reduce the amount of active ingredient used since they have a long residual life (Anderson, 1996) and some herbicides like picloram are generally too expensive to use on their own. This also helps to improve the effectiveness of the phenoxy herbicides (Rahman et al., 1994). Common mixtures include 2,4-D and picloram; and MCPA and clopyralid (O'Connor, 2004).

These herbicides, because of their superior translocation within plants (Tomlin, 2000) are excellent for application by herbicide wipers to minimise damage to pasture. Spot application of granules to rosettes e.g. Tordon 2G (20g/kg picloram amine salt) also minimises damage to pastures.

2.4.3.4 Metsulfuron-methyl

Metsulfuron-methyl (Fig 2.5) belongs to the sulfonylurea group of herbicides first developed in 1975 in the USA (Sarmah et al., 1998). The sulfonylurea molecules are composed of a phenyl group, the sulfonyl bridge, and a nitrogen-containing heterocycle such as a triazine ring which contains a methyl and a methoxy substituent. These herbicides, because of their low vapour pressures, are commonly regarded as non volatile (Sarmah et al., 1998).

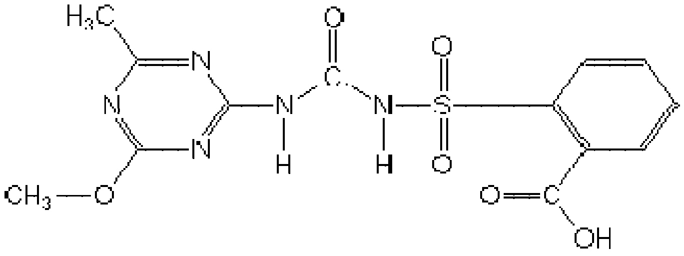


Fig 2.5 The structure of metsulfuron methyl

The herbicides in this group are effective against a wide range of broadleaf weeds and some grasses in pasture and arable crops (Sarmah et al., 1998). The herbicides have become popular because of very low product application rates of (10-40 g/ha), low mammalian toxicity and excellent herbicidal activity (Blair & Martin, 1988).

Readily absorbed by both roots and shoots of plants, metsulfuron-methyl is translocated through the xylem and phloem to meristematic regions of the plants (Anderson, 1996). Plant selectivity occurs because tolerant plants rapidly detoxify the herbicide metabolically to non-toxic metabolites. The mode of action of metsulfuron-methyl is inhibition of the enzyme acetolactate synthase (ALS) which is a catalyst in the bio-synthesis of essential amino acids valine, leucine and isoleucine thus disrupting protein synthesis (Ray, 1985).

Weed resistance to sulfonylurea herbicides in plants is associated with an altered form of the enzyme ALS. Following repeated use of the sulfonylureas, resistant biotypes of certain weeds have evolved e.g. kochia (*Kochia scoparia* L. (Schrad)), prickly lettuce (*Lactuca serriola* L.), and Russian thistle (*Salsola tragus* L.) (Anderson, 1996). Kudsk et al. (1995) have also discovered a biotype of chickweed in Denmark that is tolerant to sulfonylurea herbicides including metsulfuron-methyl. Tolerant weeds can be managed by mixing sulfonylureas with other suitable broadleaf herbicides with a different mode of action e.g. 2,4-D, dicamba, clopyralid or MCPA.

The main methods of degradation of metsulfuron-methyl are acid hydrolysis and microbial degradation, with the latter being the only pathway in alkaline soils. Hydrolysis is more rapid at a pH range of 4-7 (Sarmah et al., 1998). Being acidic in nature, the herbicide molecules become anionic at high pH and can move to a considerable depth by leaching. Research has shown half life to increase exponentially with increases in pH (Sarmah et al., 1998). Increased soil moisture and temperature may decrease the persistence (Blair & Martin, 1988).

Metsulfuron-methyl is highly toxic to pastures leading to complete removal of clovers and suppression of certain grasses including ryegrass. Re-establishment of clover and susceptible grass will be affected for some months as the herbicide has a long residual life lasting up to three months depending on conditions. Trials done in New Zealand by James et al. (1999) to measure the effect of metsulfuron methyl on white clover / perennial ryegrass pasture showed a 20-45% reduction in herbage production at 3-12 (a.i.) g/ha. Clover was completely removed for the three months duration of the experiment. Metsulfuron-methyl is generally used for spot application and is recommended for wiper application because of its excellent translocation properties.

2.4.3.5 Glyphosate

Glyphosate (Fig 2.6) is a non-selective foliar-applied herbicide that rapidly moves throughout aerial and underground parts of the plant following foliar absorption (Anderson, 1996). Once absorbed, the salt ionises and the anion becomes the herbicidally active portion. Glyphosate kills plants by inhibiting the activity of the enzyme 5-enolpyruvylshikimic acid-3-phosphate synthase (EPSP), which is necessary for the formation of the aromatic amino acids tyrosine, trytophan, and phenylalanine. These amino acids are important in the synthesis of proteins that link primary and secondary metabolism (Ashton & Crafts, 1981). EPSPS results in an accumulation of shikimate-3-phosphate, ultimately preventing synthesis of essential proteins.

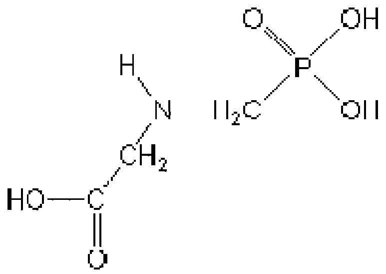


Fig 2.6 The structure of glyphosate

Glyphosate is used to control grasses, herbaceous plants including deep-rooted perennial weeds, some broadleaf trees and shrubs. Glyphosate is also a preferred herbicide for pasture renovation since it leaves no residues and translocates very well to underground perennating organs. Pastures may be renovated by complete or partial spraying with glyphosate, followed by direct drilling of seeds into a relatively weed-free environment (Haggar, 1985; Sawada et al., 1985). Glyphosate has been extensively used for wiper application because of its ability to translocate and reach underground parts of perennial weeds such as Californian thistles (McWhorter & Derting, 1985).

Being an acid, the active ingredient in glyphosate products can be formulated as salts or esters. Currently, the common salt formulations include the isopropylamine salt, trimesium ammonium and sodium salts (Baylis, 2000).

Glyphosate is strongly adsorbed by soil particles which prevent it from leaching or being taken up from the soil by non-targets plants. It is degraded primarily by microbial metabolism but strong adsorption to soil can inhibit microbial metabolism and slow degradation. Adsorption increases with increasing clay content, cation exchange capacity, decreasing soil pH and phosphorus content (Sprankle et al., 1975a, b). The adsorption of glyphosate molecules is reversible under appropriate conditions and on desorption, glyphosate is degraded by various bacteria to aminomethylphosphoric acid (AMPA) or sarcosine and ultimately to inorganic phosphate, ammonia and carbon dioxide (Baylis, 2000). A study by Thelen et al. (1995) showed that the cations of hard water, Mg^{2+} and Ca^{2+}, can greatly reduce the efficacy of glyphosate when present in spray solution. Addition of ammonium sulphate or other buffer can precipitate out heavy elements in water if added before the herbicide is mixed with water.

Several weed species have evolved resistance to different types of herbicides due to high selection pressures being exerted by repeated use of herbicides. However, despite its widespread use, only a few species have been found to be resistant to glyphosate (Baylis, 2000). These species include a biotype of rigid ryegrass (*Lolium rigidum* Gaudin.) in Australia (Powles et al., 1998) and crowsfoot grass (*Eleusine indica* (L.) (Gaertn)) in Malaysia (Lee & Ngim, 2000). More recently, several other species including hairy fleabane (*Conyza bonariensis* (L.) Cronq.)), common waterhemp (*Amaranthus rudis* Sauer.) and common ragweed (*Ambrosia artemisiifolia* L.) have developed resistance to glyphosate (Heap, 2007).

Bradshaw et al. (1997) gave several reasons for the delay in plants developing resistance including the mode of action of glyphosate, its chemical structure and metabolism as well as its lack of residual activity. The glyphosate resistance gene is now used in commercial crops to allow the use of glyphosate to control the weeds and spare the crop (Beckie et al., 2006; Rajkumara & Lamani, 2007). The development of the glyphosate resistant gene in commercial crops has ensured excellent control of a wide spectrum of weeds with a herbicide that has no soil residual activity.

2.5 Herbicide application by wipers

Wiper application allows accurate placement of herbicides onto tall and erect weeds with minimal risk to non-target vegetation (Thompson, 1983). This allows selective placement of highly effective herbicides to control weeds growing taller than the pasture. The history and design of weed wipers is further discussed in the following sections.

2.5.1 Use of weed wipers in pastures

The development of wiper applicators enabled selective use of highly effective translocated herbicides with minimal damage to pastures or desired crops by smearing the herbicide directly onto the foliage or stems of the weeds (Thompson, 1983). The discovery and development of new herbicides, including glyphosate, considered to be non-selective to most crops, and picloram, which is non-selective to broadleaf crops, resulted in increased use of wiper application (Derting, 1987). Wills et al. (1990) proposed that drift or airborne movement of herbicide onto non-target species also contributed to the development of various wiper applicators. However, these systems are only effective when the weeds are taller than the desired vegetation or crop to minimise crop damage (Gibson et al., 1984; Welker & Peterson, 1985).

The concept of wiper application involves the herbicide solution being supplied to an absorbent material that in turn smears the chemical onto the surfaces it comes in contact with. The absorbent material should be able to hold as much chemical as possible without dripping and quickly release the chemical upon contact. The wiper unit should be mounted in such a way that the height can be adjusted. Ross & Lembi (1999) described wipe-on devices as specialised pieces of equipment designed to supplement standard weed control practices. It provides the grower with another technique for attacking weeds after they have emerged above the crop, a stage of development for which there are not many satisfactory alternative techniques available. The volume of herbicides used with wipers is much less than that used with other application methods since only weed surfaces at a preset height receive herbicide (Rao, 2000).

Weed wipers do have their limitations. Prostrate weeds and those growing to a height below the wiper height, may miss treatment as the wiper passes over at a higher level (Wills et al., 1990). Other disadvantages listed include blockage of pores and/or contamination of wiper material reducing the flow and efficacy of herbicides. The use of wiper applicators during the 1970s and 1980s was limited due to a number of factors including their inability to apply adequate herbicide to weeds in dense infestations and dripping of damaging herbicide onto pastures (Makepeace & Thompson, 1982). There were also a limited number of herbicides recommended for use with weed wipers. The use of 2,4-D, MCPA and MCPB to control Californian thistle using weed wipers produced poor results (Meeklah & Mitchell, 1984). The phenoxy herbicides used do not translocate within the plant as well as other herbicides like clopyralid, triclopyr, picloram or glyphosate.

2.5.2 History and development of herbicide wiper applicators

The use of wipe-on pesticide applicators in the USA originated in the early 1900s when a horse-drawn device was used to apply insecticide solutions to plant foliage by means of wicks and absorbent material (McWhorter & Derting, 1985). The device used capillary action to transfer the insecticide through wicks onto plant foliage as it moved through the field. There were many developments through the 1920s including the use of rotating drums mounted on horse-drawn ploughs.

Herbicides were not used with wipe-on applicators for selective weed control in crops until the commercial development of 2,4-D and other phenoxy herbicides in the late 1940s (McWhorter & Derting, 1985b). The most common method used by farmers was wrapping the spray-boom with an absorbent material to apply 2,4-D as the spray-boom moved through the field. The boom was held a few centimetres above the crop but in contact with the taller weeds. The use of this technology was very limited due to the lack of selectivity of 2,4-D on dicotyledons (Wills & McWhorter, 1981a).

There was a phenomenal increase in the availability of wiping devices in the USA in the 1970s triggered by the problem of tall weeds such as Johnson grass (*Sorghum halepense* (L) Pers.) in cotton (*Gossypium hirsutum* L.) and soybeans (*Glycine max* (L) Merr) which were not fully controlled by available herbicide treatments (Davison & Parker, 1983). Since the registration of glyphosate in the mid-1970s, various weed wipers that were specifically designed to apply this non-selective, translocatable herbicide evolved treating up to eight million hectares in crops in the USA alone (Blank, 1981). By 1979, farmer interest in the USA had grown so much that more than 26 000 rope-wick applicators were sold in one year with individual farmers constructing an equal number themselves (Wills & McWhorter, 1981a). Wiping devices were adopted for use in New Zealand pastures for the control of thistles, ragwort

(*Senecio jacobaea* L.) and rushes (*Juncus* spp.) among other weeds in the 1970s (Makepeace & Thompson, 1982).

2.5.3 Design of early rope-wick and roller applicators

The two main types of wiper applicators developed in the late 1970s included either roller or wick devices. The design and performance of these two types are further discussed in the following sections.

2.5.4.1 Rope–wick applicators

One of the first commercially developed weed wipers include the Stoneville rope-wick applicator. The Stoneville rope-wick applicator invented by J E Dale in 1978 in the U.S.A uses capillary nylon rope wicks where the chemical is rubbed from the soaked rope onto tall weeds (Rao, 2000). The rope-wick utilises a herbicide-wetted nylon fabric, or other abrasion resistant material or combination of materials, braided into a rope and mounted on a vehicle, with different forms that vary in the composition and arrangement of the rope wicks and the manner in which the aqueous herbicide solution wets the wicks. The herbicide is placed inside a PVC pipe and braided ropes are used to wick out the solution. The reservoir continuously supplies the wicks with herbicide which is in turn smeared on to the weeds. The use rate of the herbicide is therefore related to the weed density. This minimises off-target damage as the wicks smear the chemicals on to the weeds without any drift.

Moore & Jones (1988) described the two common types of rope-wick as transverse and longitudinal applicators based on the inclination of the wicks relative to the PVC beam. The transverse applicator (Fig 2.7) consists of a long horizontal tube with multiple wicks along its length. This can be towed by a tractor or All Terrain Vehicle (ATV). A conventional vehicle can also be used to tow the boom in some cases.

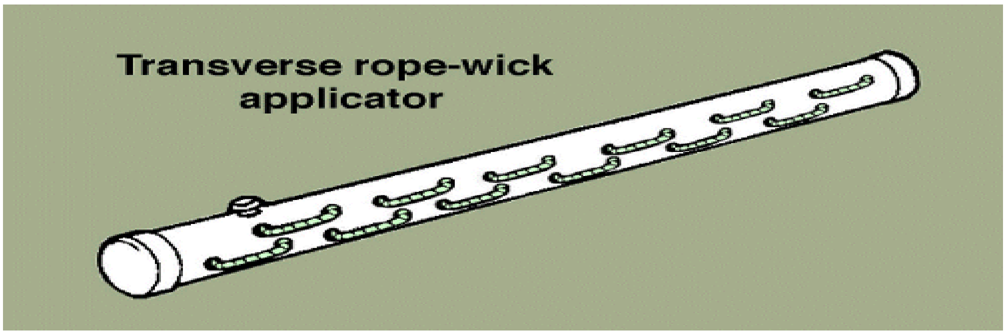


Fig 2.7 Transverse rope-wick applicator
(Source: www.agric.wa.gov.au)

The longitudinal applicator (Fig 2.8) has a rectangular frame with the ropes attached to the two main frames at an angle. This arrangement provides a long contact time between the wicks and individual plants.

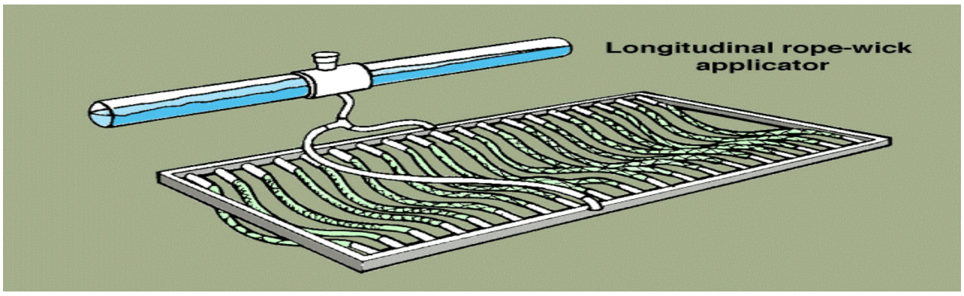


Fig 2.8 Longitudinal rope-wick applicator
(Source: www.agric.wa.gov.au)

Ropes used in the Stoneville rope-wick applicator were 13mm in diameter and solid braided of continuous filament nylon (Derting, 1987). Nylon was chosen for its strength compared to other fibres but had its own weaknesses such as shrinkage upon drying leading to a reduction in capillary space and herbicide flow. The abrasion resistance of nylon fibre was also significantly reduced when wet.

Alternative fibres used in other applicators include acrylic, cotton, polyester, propylene and polyester over acrylic diamond braid. The type of rope has a significant effect on performance as it determines the rate of flow and load of the herbicide available to the target weed. The following fibre properties were considered in choosing the most appropriate wick material: shrinkage, abrasion resistance, load capacity, stretchability, biodegradability and strength (Derting, 1987).

There have been many variations of rope wick applicators from simple to multiple wick applicators as well as from passive to pressurised types (McWhorter & Derting, 1985). The differences in the arrangement of ropes also led to differences in performance. According to Derting (1987), the longitudinal multiple rope wick applicators proved superior to the simple Stoneville type in the control of Johnson grass and other weeds in single pass applications regardless of speed. This is presumably due to greater number of wick-feeder openings and greater surface area per unit of length.

2.5.4.2 Roller applicators

The roller applicators have the same basic principle as the rope-wick but instead of using ropes to wick out the herbicide, the solution is trickled onto a carpet-covered roller that is rotated by a small motor as the applicator is driven across the field (Ozkan, 1995). The roller rotates counter-clockwise to the direction of travel and this minimises drippage (Schneider et al., 1982). The carpet on the early models was wetted manually by switching the valve on and off to maintain a desired level of wetness without dripping (Ozkan, 1995; Toor & Brewster, 1995).

The roller usually comprises a 20-25 cm aluminium cylinder covered with an absorbent material of nylon carpet (Derting, 1987). The roller can either be front or rear mounted on the tractor with the latter being the most common. The carpet-covered aluminium cylinder is usually 3-9 metres long. A plastic or steel tubing mounted above the roller with holes drilled 2.5-5 cm apart is used to apply herbicide to the carpet.

The main problem of rotary weed wipers in the 1980s was that the manual dispensing of herbicide onto the carpet by a farmer-operated pump caused difficulties in judging how much herbicide to apply onto the carpet and this often led to either over- or under-application of the herbicide (Schneider et al., 1982; Toor et al., 1994). The other problem occurred when the operator was distracted by looking behind to check on the level of wetness of the roller and level of solution in the tank. However, improvement in technology has led to the development of electronic systems which sense the moisture level on the roller and automatically regulate the flow of the herbicide (Schepers & Burnside, 1979; Toor et al., 1994).

The roller applicators in the USA are normally operated at speeds of 3-6 km/hr and like the rope-wick applicator, the speed is dependent on several factors including the level of weed infestation (Derting, 1987). Performance may be improved by reducing the speed in areas of heavy weed infestations to ensure good leaf coverage. Also, better results may be obtained if two applications are made in opposite directions. In later models of weed wipers, herbicide penetration especially in woody perennials has been enhanced by abrasive bars or blades (to abrade the foliage) mounted in front of the roller.

2.6 Performance of selective wiper applicators

There are various design factors that influence the performance of wipe-on applicators. These factors include type of wiping material, number of passes and speed, dilution rates and herbicide output, and are described below.

2.6.1 Pressure and gravity

There is a difference in the amount of herbicide dispensed by passive and active pressurised systems. Herbicide recharge in the passive systems is faster when the reservoir is placed above the wicks creating pressure on the solution (Derting, 1987), while herbicide flow in the active systems is generally controlled manually by switching the valve on and off.

The major problems with passive systems are insufficient herbicide being applied to target weeds, and non-uniformity of application especially on uneven ground where the herbicide solution moves inside the tilted applicator (Wills & McWhorter, 1981b). In the event of a tilt, the lower side of the wiper will receive excessive herbicide that can lead to dripping and consequently pasture damage while the upper end dries off leading to insufficient application (McWhorter & Derting, 1985).

Pressurised designs evolved to counter some of the problems experienced with passive systems. The pressurised applicators provided an improvement in regulating herbicide control by adjusting the pressure to suit the task, based mainly on weed density (Derting, 1987).

The objectives of the active flow systems were to: increase wicking efficiency; decrease recharge time required in wiping continuous vegetation; maintain uniformity of application on uneven terrain; prevent dripping; and increase activity on more difficult to control species (Derting, 1987). Improved designs however led to increased costs and maintenance. Dale (1980) pointed out that since pumping systems contain moving parts, they consume energy making them more expensive than the rope-wick applicators that use gravitational flow of the herbicide. Despite all the improvements, results from the field using weed wipers have been variable pointing to the need to further improve their design and increase their performance.

2.6.2 Number of trips and speed

Some experiments have been done with both roller and rope-wick applicators to determine the effect of ground speed in a single and double pass at various herbicide concentrations. Wu & Derting (1981) found that control of Johnson grass was usually improved with a double pass while increasing speed from 3.75 to 7.5 km/hr generally reduced the level of control.

Martin et al. (1990) used a rotary weed wiper to control Californian thistle (*Cirsium arvense* (L.) Scop.), nodding thistle (*Carduus nutans* L.), ragwort, rushes (*Juncus* spp.) and oxeye daisy (*Chrysanthemum leucanthemum* L.) with different herbicides. They found no difference between a single and a double pass or between a ground speed of 5 and 10 km/hr. Dense stands of weeds were well controlled showing that the rotary weed wiper was depositing enough herbicide in a single pass, or at a faster speed, making a double pass unnecessary.

Lutman et al. (1982) measured the amount of glyphosate deposited on weeds using one rope-wick and two roller applicators. There was no difference in the amount of herbicide deposited by changing the speed from 1.5 to 6 km/hr with one roller applicator and the rope-wick device. However, there was a significant difference in the amount deposited by the second roller applicator. There was no obvious reason for the difference in output for the two roller weed wipers. However, one of the rollers was electrically driven at 21 revs/min while the other was manually driven and the possible difference in rotational speed could explain the difference. A study by Welker & Peterson (1987) showed an increase in the level of control of weeds when the rotational speed of a rotary weed wiper was increased.

Moore & Jones (1988) investigated the effect of speed and number of passes to control bracken fern (*Pteridium aquilinum* var. *esculentum* (L) Kuhn) in pastures using a longitudinal and transverse rope-wick applicator and glyphosate. They found that a double pass was always better than a single pass. They also found that there was approximately 50 % kill with each pass with the transverse applicator, whilst with the longitudinal applicator there was approximately 85 % control with each pass. Thus, one pass with a longitudinal applicator gave similar results to a double pass with the transverse applicator.

2.6.3 Type of rope and absorbent material

The type of rope has an effect on the performance of the wiper as it determines the rate of flow and load of the herbicide available to the weed (Derting, 1981a). The capillary action of the herbicide could be improved by altering the inclination of the ropes from the 3 o’clock position to the 5 o’clock position (Wu & Derting, 1981). This presumably meant ropes at a 3 o’clock position were facing directly forwards, half way down the face of the boom as on a clock, whereas 5 o’clock was facing downwards but not totally underneath the boom. This improvement resulted from increased head pressure on the reservoir and led to a two-fold difference in the control of Johnson grass. However, this inclination caused crop damage due to excessive dripping.

Derting (1980) evaluated the effect of length of rope on the control of Johnson grass in soybeans using glyphosate. Rope lengths of 10 cm, 15 cm, and 20 cm resulted in 75, 50, and 40 % control, respectively, from one pass at 5 km/hr. The experiment was repeated with a double pass and the 10 cm, 15 cm and 20 cm resulted in 75, 75 and 50 % control, respectively. Poor control with a longer rope was due to slow recharge time and reduced capillarity.

2.6.4 Herbicide type, concentration and formulation

Lueschen et al. (1980) compared the wicking rates of glyphosate and 2,4-D at various concentrations using a nylon rope. Glyphosate was found to have a much higher wicking rate than that of 2,4-D amine which was also higher than that of 2,4-D ester. There was a steep linear decline in wicking rates as the concentration increased for all herbicides with no wicking of either formulation of 2,4-D at 50 or 67 % concentration. Increase in concentration probably increases the viscosity of the herbicide solution thereby reducing its ability to flow.

2.6.5 Operator skills

Toor et al. (1994) compared the amount of herbicide dispensed by automated and manual Dinkum rotary weed wipers using experienced farmers to operate the manual devices. There were no differences except that there was more fatigue in the farmers using the manual devices. However, the farmers agreed that the automated type reduced guesswork in how much to apply and ensured more consistent application of the herbicide.

2.7 Herbicide applicators used in New Zealand

Although there have been significant developments in the type of weed wipers since the early 1970s to the present, weed wipers that rely on manually-operated pumps still dominate the market. Although pumps in some wiper applicators such as the Eliminator have some automation, they simply turn the pump on and off at preset times, not in response to wetness of the wiper pads. Moisture sensors do regulate pumping of herbicide on to pads in the Weedswiper, though these are located at only two points on the boom and might not be representative of the overall wetness of the boom. Variable research results regarding the effect on weed control of speed and number of passes of wipers have not been linked to the moisture level of wiper pads, which is difficult to measure. There are various types of herbicide wiper applicators used in New Zealand as described below.

2.7.1 Wick boom

The Winstone type wick-boom applicator has been in use since the early 1980s in New Zealand (Haydon, 1983). Rushes have been controlled successfully using glyphosate applied by wick booms on many New Zealand farms. Haydon (1983) stated that rushes should be treated with a double pass if they occupy more than 30 % of the ground space but that a single pass will suffice if a smaller amount of the ground is occupied. However, a single application needs a follow-up treatment after 12 months to ensure good control.

A common problem with wick booms is that some are too wide for some farm gates and bridges making it impossible to access all paddocks. Haydon (1983) cited some of the errors by farmers which reduced the efficiency of the Winstone wick boom: incorrect height setting; incorrect setting of screw cap flow adjustment; wrong speed; and failure to use appropriate herbicide dilution rates.

Technological developments led to improved wick booms with folding arms e.g. the Te Pari 4 m wick boom. This type of boom folded into two reducing its width to 2.2 m for travelling, was towed behind a bike and its height could be adjusted from 10 cm to 40 cm.

2.7.2 Weedswiper

The Weedswiper (Plate 2.1), originally manufactured in Australia by Agtronix and marketed throughout Australasia, has been used to control tall growing weeds in susceptible crops since the early 1980s.

Plate 2.1 The Weedswiper (arms being folded) used in the experiment

The Weedswiper uses an electronic control system to regulate herbicide flow in response to changes in weed density (Royston et al., 2004; Willis & Dalgleish, 1986). The sensor, located in the swiping pad material, senses the amount of fluid contained within the pad material. This takes place continually throughout the time the unit is in work. The sensors send a signal to the hydrostat controller when more fluid is required in the pad material, which maintains a constant saturation level. The hydrostat then sends a signal to the pump to allow more fluid to flow to the pad as required.

The hydrostat is set by increasing the wetting until the wiper material drips, then easing the setting back a little to bring the absorbent material to just under the threshold level. This allows for maximum wetness without dripping. The Weedswiper with its reversible booms can be either front or rear mounted on a tractor, ATV or a conventional four-wheel-drive vehicle. The effective working width of the boom ranges from 2.3 m to 4.7 m and is adjustable.

2.7.3 Z-Wiper and Eliminator

The Z-Wiper and Eliminator (Plate 2.2) are manufactured by C-Dax (New Zealand) and are both ATV mounted. The Eliminator is an improvement on the Z-Wiper which it replaced. The original Z-Wiper had 3 sizes of varying widths ranging from 2.2 m; 3.0 m to 6.4 m. The first two were of fixed length while the trailed 6.4 m model could be folded. The Z wiper had a rectangular design with all the wiping carpets facing one direction. The Eliminator comes in one size with effective wiping width of 2.35 m. However, the wiping width can be increased by coupling together individual units to 4.7 m and 7.0 m for two and three wipers respectively (Plate 2.2).

The Z-Wiper and Eliminator both have wiper arms set at an angle to increase the surface area for wiping weeds. Both wipers are fitted with bruise bars to aid herbicide penetration. Each arm is fed with a herbicide solution using a pressurised system. An electronic controller is used to regulate the flow of the herbicide and maintain the wetness of the arms regardless of terrain (C-Dax, 2007). The operator has to determine the level at which the electronic controller is set depending on weed density. This necessitates some skill in the operation of the device.

The Eliminator has a “delta” design with wiping carpets fitted on opposing angles. This, according to C-Dax, maximises plant contact and improves weed control (Graeme Gates, 8 August 2005, *personal communication*). The Eliminator has four wiping heights and a variable wheel configuration in addition to most of the functions of the Z-Wiper.

Plate 2.2 Three Eliminator wipers joined together
(Source: www.cdax.co.nz)

2.7.4 Rotowiper

The Rotowiper (Plate 2.3) is a roller type herbicide applicator (2.4.2). The roller is covered by an absorbent carpet on a rotating drum. The carpet is wetted by means of a 12-volt electrical pump. The effective width of the wiper ranges from 2.9 m – 6.0 m depending on the model and has the ability to work at different heights (Rotoworks, 2007).

The weeds exert pressure on the carpet thereby squeezing the chemical onto the foliage and stem. The bigger the weed, the more pressure exerted and hence more herbicide applied. The Rotowiper has a manually operated switch to regulate the flow of herbicide which the operator must activate according to the level of infestation. The optimum ground speed depends on the density of weeds but is generally around 10 km/hr.

Foam and dye marker systems aid uniform spray application by marking the edge of the spray swath. The foam or dye requires a separate tank and mixer, a pump and delivery tube to each end of the boom.

Plate 2.3 The Rotowiper similar to the one used in the trials
(Source: www.rotoworks.co.nz)

2.8 Conclusions

Pasture weeds are a problem and killing them with a wider range of herbicides would be beneficial to farmers. Several highly effective herbicides can be made selective by using weed wipers, but currently not much work has been done on them. Also, spot-spraying these herbicides will minimise damage to pasture although there is a need for research to quantify this damage. The key issues to be explored further in this study include developing a technique to measure herbicide output from weed wipers and investigate their performance under different scenarios such as speed and wetness of the pads. The study will also explore ways of increasing the precision of applying herbicides during spot spray as a way of minimising pasture damage.

2.9 References

AHMED M & WARDLE DA (1994) Allelopathic potential of vegetative and flowering ragwort (*Senecio jacobaea* L.) plants against associated pasture species. *Plant and Soil* **164**, 61-68.

ALDRICH RJ & KREMER RJ (1997) Principles in weed management. Ames: Iowa State University Press, Belmont.

ANDERSON WP (1996) Weed Science: Principles and Applications. West Publishing Company, USA.

ASHTON FM & CRAFTS AS (1981) Mode of action of herbicides. John Wiley & Sons, New York.

BAYLIS AD (2000) Why glyphosate is a global herbicide: strengths, weaknesses and prospects. *Pest Management Science* **56**, 299-308.

BECKIE HJ, HARKER KN, HALL LM et al. (2006) A decade of herbicide-resistant crops in Canada. *Canadian Journal of Plant Science* **86**, 1243-1264.

BLAIR AM & MARTIN TD (1988) A review of the activity, fate and mode of action of sulfonylurea herbicides. *Pesticide Science* **22**, (**3**), 195-219.

BLANK SE (1981) Selective equipment to apply glyphosate. In: *Proceedings 1981 Annual Meeting Southern Weed Science Society*,**1**, 300.

BOURDOT GW, FOWLER SV, EDWARDS GR et al. (2007) Pastoral weeds in New Zealand: status and potential solutions. *New Zealand Journal of Agricultural Research* **57**, 139-161.

BOURDOT GW (1996) Interference between pasture plants and thistles - a review. *Plant Protection Quarterly* **11**, 267-269**.**

BOURDOT GW, FOWLER SV, EDWARDS GR et al. (2007) Pastoral weeds in New Zealand: status and potential solutions. *New Zealand Journal of Agricultural Research* **57**, 139-161.

BOURDOT GW & SAVILLE DJ (2002) Estimating economic losses due to pasture weeds. In: P*roceedings* 2002 *New Zealand Plant Protection Conference*, Rotorua, New Zealand, 106-110.

BOVEY RW (1995) Weed management systems for rangeland. In: *Handbook of Weed Management Systems* (ed. AE Smith), 519-552. Marcel Dekker, New York.

BRADSHAW LD, PADGETTE SR, KIMBALL SL & WELLS BH (1997) Perspectives on glyphosate resistance. *Weed Technology* **11**, 189-198.

BUCHHOLTZ KP (1967) Report of the terminology committee of the Weed Science Society of America. *Weeds* **15**, 388-389.

CAST (1975) The phenoxy herbicides. *Weed Science* **23**, 253-263.

C-DAX (2007) Weed wiper - product range. [Online]: Available: http://www.cdax.co.nz/efx/include/common/category.asp?country=AU&CatID=21 [Retrieved 21 November 2007].

CHANG FY & VANDERN BORN WH (1971) Dicamba Uptake, translocation, Metabolism and Selectivity. *Weed Science* **19**, 113-117.

COMBELLACK JH (1981) The problems involved in improving spraying efficiency. *Australian Weeds* **1**, 13-18.

COUSENS R (1987) Theory and reality of weed control thresholds. *Plant Protection Quarterly* **2**, 13-20.

COUSENS R, WILSON BJ & CUSSANS GW (1985) To spray or not to spray: the theory behind the practice. In: *Proceedings British Crop Protection Conference, Weeds* **2**, 671-678.

DALE JE (1980) Rope wick applicator - Tool with a future. In: *Weeds Today*. **11**, 3-4.

DAVISON JG & PARKER C (1983) The potential of rope-wick devices for direct contact application of herbicides in small-scale farming in the tropics. *Tropical Pest Management* **29, (1)**, 47-51.

DERTING CW (1980) Response to operational factors which influence rope wick effectiveness. In: *Proceedings North Central Weed Control Conference,* **35***,* 63.

DERTING CW (1981a) Correlation of rope wick design and components with glyphosate performance. In: *Proceedings 1981 Annual Meeting Southern Weed Science Society*, Dallas, 305-310.

DERTING CW (1981b) A proposal for standardization and measurement of rope wicking properties. In: *Proceedings 1981 Annual Meeting Southern Weed Science Society*, Dallas, 301-304.

DERTING CW (1987) Wiper application. In: *Methods of applying herbicides* Vol. 4 (eds CG McWhorter. & MR Gebhardt.), 207-229. Weed Science Society of America, USA.

DOWLING PM, MICHALK DL & SINDEL BM (2000) Weed management in pasture systems. In: *Australian Weed Management Systems* (ed. BM Sindel), 307-328. R. G. and R. J. Richardson, Melbourne.

DOYLE P & STYPA M (2004) Reduced herbicide rates - a Canadian perspective. *Weed Technology* **18**, 1157-1165.

EDMONDS DK, SANDERS P & POPAY AI (1982) Clover defoliation before spraying with 2,4-D and its effect on clover recovery. In: *Proceedings 1982 New Zealand Weed and Pest Control Conference*, Hamilton, New Zealand, 75-78.

EERENS JPJ, RAHMAN A & JAMES TK (2002a) Optimising pasture production to minimise weed growth. In*: Proceedings of the New Zealand Grassland Association* **64**, 143-146.

EERENS JPJ, SEEFELDT SS, GARRY G & ARMSTRONG ML (2002b) Controlling Californian thistle (*Cirsium arvense*) through pasture management. In: *Proceedings 2002 New Zealand Plant Protection Conference,* Rotorua, New Zealand, 111-115.

GIBSON HG, GAULTNEY LD, HOLT HA & KRUTZ GW (1984) Roller-wiper herbicide applicator: control of right-of-way hardwood brush. *Journal of Arboriculture* **10,** 71-82.

GRICE AC & CAMPBELL SD (2000) Weeds in pasture ecosystems - symptom or disease? *Tropical Grasslands* **34**, 264-270.

HAGGAR RJ (1985) Efficacy of glyphosate for weed control in grassland, turf grass and amenity grassland and for renovation of pastures. In: *The herbicide glyphosate* Butterworths, London, UK.

HAGGAR RJ, SOPER D & CORMACK WF (1990) Weed control in agricultural grassland. In: *Weed Control Handbook: Principles* (eds RJ Hance & K Holly), 8th edn, 387-405. University Press, Cambridge.

HARRINGTON KC (1989) Distribution and cross-tolerance of MCPA-tolerant nodding thistle. In: *Proceedings 1989 New Zealand Weed and Pest Control Conference,* Palmerston North, New Zealand, 39-42.

HARRINGTON KC (1996) Herbicide management and thistle control - how to avoid resistance. *Plant Protection Quarterly* **11**, 273-275.

HARRINGTON KC & IVENS GW (1983) The influence of growth stage and application site on Californian thistle control by glyphosate. In: *Proceedings 1983 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 99-103.

HARRINGTON KC, THATCHER A & KEMP PD (2006) Mineral composition and nutritive value of some common pasture weeds. In: *Proceedings* 2006 *New Zealand Plant Protection*, Blenheim, New Zealand, 261-265.

HARTLEY MJ (1983) Effect of Scotch thistles on sheep growth rates. In: *Proceedings* 1983 *New Zealand Plant Protection Conference*, Hastings, New Zealand, 86-88.

HARTLEY MJ & ATKINSON GC (1978) Cost benefit of barley grass control. In: *Proceedings 1978 New Zealand Weed and Pest Control Conference* **31**, New Plymouth, New Zealand, 245-249.

HARTLEY MJ & JAMES TK (1979) Cost benefit of selective control of Californian thistle in pasture. In: *Proceedings 1979 New Zealand Weed and Pest Control Conference* **32**, Dunedin, New Zealand, 245-249.

HAYDON A (1983) Wick booms have strengths and weaknesses. *New Zealand Journal of Agriculture* **146**, 8-9.

HEAP I (2007) The International Survey of Herbicide Resistant Weeds. [Online]: Available: www.weedscience.com [Retrieved 20 December 2007].

JAMES TK, RAHMAN A & CORNWELL MJ (1999) Pasture tolerance to the herbicide metsulfuron-methyl. In: *Proceedings 1999 New Zealand Plant Protection Conference*, Auckland, New Zealand, 240-244.

JAMES TK, RAHMAN A & JONG PD (1997) Flazasulfuron for control of ragwort (*Senecio jacobaea*) in pasture. In: *Proceedings 1997 New Zealand Plant Protection Conference,* Lincoln University, Canterbury, New Zealand, 477-481.

JONES RE (2000) The economics of weed control. In: *Australian weed management systems* (ed. BM Sindel), 267-283. R.G and R.J Richardson, Melbourne.

KEARNEY PC & KAUFMAN DD (1975a) Herbicides: chemistry, degradation, and mode of action. In: *Herbicides: chemistry, degradation and mode of action.* Vol. 1 Marcel Dekker Inc., New York USA.

KEARNEY PC & KAUFMAN DD (1975b) Herbicides: chemistry, degradation and mode of action. In: *Herbicides: chemistry, degradation and mode of action.* Vol. 2 Marcel Dekker Inc., New York USA.

KEMP PD, MATHEW C & LUCAS RJ (2000) Pasture species and cultivars. In: *New Zealand pasture and crop science* (eds J White & J Hodgson), 84-99. Oxford University Press, Melbourne.

KEMPENAAR C, GROENEVELD RM, UFFING AJ & WEIDE R (2002) New insights and developments in the MLHD-concept of weed control. In: *Proceedings 2002 European Weed Research Society Symposium*, 98-99.

KLINGMAN GC & ASHTON FM (1982) Weed Science: principles and practices. John Wiley & Sons, New York.

KUDSK P, MATHIASSEN SK & COTTERMAN JC (1995) Sulfonylurea resistance in *Stellaria media* L. Vill. *Weed Research (Oxford)* **35**, 19-24.

LEATHWICK DM & BOURDOT GW (1991) Application time influences the development of herbicide resistance in giant buttercup (*Ranunculus acris)*. In: *Proceedings 1991 New Zealand Weed and Pest Control Conference,* Tauranga, New Zealand, 275-279.

LEE L & NGIM J (2000) A first report of glyphosate-resistant goose grass (*Eleusine indica* (L) Gaertn) in Malaysia. *Pest Management Science* **56**, 336-339.

LUESCHEN WE, FURRER JD & MARTIN AR (1980) A comparison of wicking rates of soft braid nylon rope for glyphosate and 2,4-D. In: *Proceedings North Central Weed Control Conference,* ***35****,* 61-62.

LUTMAN PJW, OSWALD AK & BYAST TH (1982) The chemical estimation and biological activity of glyphosate deposited on four plant species by one rope wick and two roller applicators. In: *Proceedings 1982 British Crop Protection Conference: Weeds,* Brighton, UK, 1001-1008.

MAKEPEACE W & THOMPSON A (1982) Ragwort control using a rope wick applicator. In: *Proceedings 1982 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 256-260.

MARTIN P, FULLERTON DK & JAMES TK (1990) Weed trials using a rotary weed wiper. In: *Proceedings 1990 New Zealand Weed and Pest Control Conference*, Dunedin, New Zealand, 262-265.

MARTIN P, THOMPSON A & RAHMAN A (1988) Spot treatment of ragwort and nodding thistle with DPX-L5300. In: *Proceedings 1988 New Zealand Weed and Pest Control Conference,* Auckland, New Zealand, 223-225.

MATTHEWS PNP, HARRINGTON KC & HAMPTON JG (2000) Management of grazing systems. In: *New Zealand pasture and crop science* (eds J White & J Hodgson), 153-174. Oxford University Press, Melbourne.

MCWHORTER CG & DERTING CW (1985) Methods of application of glyphosate. In: *The herbicide glyphosate*, Butterworths, London UK.

MEEKLAH FA & MITCHELL RB (1984) Evaluation of herbicides for control of Californian thistle. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 20-23.

MOORE JH & JONES SM (1988) Bracken control with rope-wick applied glyphosate. *Plant Protection Quarterly* **3**, 65-68.

MOORE WB, DOYLE CJ & RAHMAN A (1989) Economics of controlling *Carduus nutans* on grazed pasture in New Zealand. *Crop Protection* **8**, 16-24.

MORTIMER AM (1990) The biology of weeds. In: *Weed control handbook: Principles* (eds RJ Hance & K Holly), eighth edn, 1-42. Blackwell Scientific Publications, Oxford.

O'CONNOR B (2004) Novachem Manual 2004/2005. In: *Novachem Manual* (Novachem Services Limited), Palmerston North 488 pp.

OZKAN EH (1995) Herbicide application equipment. In: *Handbook of weed management systems* (ed. AE Smith), 155-216. Marcel Dekker, New York.

PANNELL DJ (1987) Weed control economics research in Australia. *Australian Weeds Conference* **8**, 1-11.

POPAY AI, BARLOW ND & BOURDOT GW (1989) Economics of controlling *Ranunculus acris* in New Zealand dairy pastures. In: *Proceedings 1989 Brighton Crop Protection Conference, Weeds* **3**, 943-948.

POPAY AI & THOMPSON A (1980) Nodding thistle: its growth and control. In: *Proceedings 1980 Ruakura Farmers' Conference,* Ruakura, New Zealand, 63-69.

POWLES SB, LORRAINE-COLWILL DF, DELLOW JJ & PRESTON C (1998) Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum)* in Australia, *Weed Science* **46**, 604-607.

RAHMAN A, JAMES TK & SANDERS P (1994) Control of phenoxy herbicide resistant nodding thistle (*Carduus nutans*) in pasture. In: *Proceedings 1994 New Zealand Plant Protection Conference,* Waitangi, New Zealand, 68-74.

RAHMAN A, MANSON BE & SANDERS P (1981) Persistence of 3,6-dichloropicolinic acid and dicamba residues in the soil. In: *Proceedings 1981 New Zealand Weed and Pest Control Conference,* Blenheim, New Zealand 126-129.

RAJKUMARA S & LAMANI KD (2007) Weed management in herbicide resistant crops - a review. *Agricultural Reviews* **28**, 56-62.

RAO VS (2000) Principles of weed science. In: *Principles of weed science.* (Science Publishers Inc., Enfield, USA.

RAY TB (1985) The site of action of the sulfonylurea herbicides. *In: Proceedings British Crop Protection Conference: Weeds* **1**, 131-138.

ROSS MA & LEMBI CA (1999) Applied weed science. Prentice Hall.

ROTOWORKS (2007) Rotowiper. [Online]: Available: http://www.rotowiper.co.nz/Using.htm [Retrieved 21 August 2007].

ROYSTON T, CHRISTIAN CB & MADDOCKS T (2004) A novel, none drip, supply on demand Weedwiper for targeted application of herbicides to tall weeds in arable, fruit and grassland crops. *Aspects of Applied Biology*, **71, (1)**, 267-268.

SARMAH AK, KOOKANA RS & ALSTON AM (1998) Fate and behaviour of triasulfuron, metsulfuron-methyl, and chlorsulfuron in the Australian soil environment: a review. *Australian Journal of Agricultural Research* **49 (5)**, 775-790.

SAWADA M, KUNEZAKI K & JANUMA T (1985) Renovation of deteriorated pasture by surface sowing renovation of pasture with glyphosate herbicide and burning. In: *Proceedings 1985 International Grassland Congress,* Kyoto, Japan, 567-568.

SCHEPERS JS & BURNSIDE OC (1979) Electronic moisture sensor for maintaining herbicide solution on a roller applicator. *Weed Science* **27**, 559-561.

SCHNEIDER GL, KOEHLER CB, SCHEPERS JS & BURNSIDE OC (1982) Roller applicator for shattercane (*Sorghum bicolor*) control in row crops. *Weed Science* **30**, 301-306.

SEEFELDT SS, STEPHENS JMC, VERKAAIK ML & RAHMAN A (2005) Quantifying the impact of a weed in a perennial ryegrass-white clover pasture. *Weed Science* **53**, 113-120.

SMITH AE (1990) Potential allelopathic influence of certain pasture weeds. *Crop Protection* **9**, 410-414.

SMITH AE & MARTIN LD (1995) Weed management systems for pastures and hay crops. In: *Handbook of Weed Management Systems* (ed. AE Smiths), 477-518. Marcel Dekker, New York.

SPRANKLE P, MEGGITT WF & PENNER D (1975a) Adsorption, mobility and microbial degradation of glyphosate in the soil. *Weed Science* **23**, 229-234.

SPRANKLE P, MEGGITT WF & PENNER D (1975b) Rapid inactivation of glyphosate in the soil. *Weed Science* **23**, 224-228.

STACHON WJ & ZIMDAHL RL (1980) Allelopathic activity of Canada thistle (*Cirsium arvense*) in Colorado. *Weed Science* **28**, 83-86.

SWARBICK JT (1981) How much of your spray hits the target? *Australian Weeds* **1**, 2.

TAYLOR RL (1973) Control of ragwort. In: P*roceedings 1973 New Zealand Weed and Pest Control Conference*, Auckland, New Zealand, 50-52.

THELEN KD, JACKSON EP & PENNER D (1995) The basis for the hard-water antagonism of glyphosate activity. *Weed Science* **43**, 541-548.

THOMPSON A (1983) Pasture weed control by rope wick applicator. In: P*roceedings 1983 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 96-98.

THOMPSON A & SAUNDERS A (1984) A comparison of 2,4-D and MCPA, alone and in combination, for the control of ragwort. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 33-36.

TOMLIN CDS (2000) The Pesticide Manual. In: *A World Compendium*. British Crop Protection Council, Surrey, UK.

TOOR RF, MITCHELL RB & ABERNETHY RJ (1994) Evaluation of an automatic herbicide dispenser for rotary weed wipers. In: *Proceedings 1994 New Zealand Plant Protection Conference,* Rotorua, New Zealand, 84-87.

TOOR RF VAN & BREWSTER DS (1995) Automatic herbicide dispenser for rotary wipers. Applied Engineering in Agriculture **11, (3)**, 377-380.

TOOR RF VAN & STUCK RJ (1993) Farmers evaluation of weed and invertebrate pest problems in pasture. In: *Proceedings 1993 New Zealand Plant Protection Conference,* Christchurch, New Zealand, 200-205.

WARDLE DA (1987) The ecology of ragwort (*Senecio jacobaea* L.) - a review. *New Zealand Journal of Ecology* **10**, 67-76

WARDLE DA, NICHOLSON KS & RAHMAN A (1993) Influence of plant age on the allelopathic potential of nodding thistle (*Carduus nutans* L.) against pasture grasses and legumes. *Weed Research (Oxford)* **33**, 69-78.

WELKER WV, JR. & PETERSON DL (1985) The rotary herbicide wiper. *Weeds Today* **16**, 4.

WELKER WV, JR. & PETERSON DL (1987) A rotary herbicide wiper for post-emergence weed control in perennial horticultural crops. *Weed Technology* **1**, 319-322.

WILLIAMS RD (1984) Crop protection handbook - grass and clover swards. The British Crop Protection Council, Croydon.

WILLIS BG & DALGLEISH P (1986) Weedswiper. *Plant Protection Quarterly* **1**, (**3**) 124.

WILLS BG, CAMPBELL MM & FLEMING D (1990) Evaluation of a brush wiper for application of herbicides. In: *Proceedings 1990 Australian Weeds Conference, 317-325.*

WILLS GD & MCWHORTER CG (1981) Developments in post-emergence herbicide applicators. *Outlook on Agriculture* **10**, 337-341.

WILSON RG & MICHIELS A (2003) Fall herbicide treatments affect carbohydrate content in roots of Canada thistle (*Cirsium arvense*) and dandelion (*Taraxacum officinale*). *Weed Science* **51**, 299-304.

WU CH & DERTING CW (1981) Operational variables and glyphosate performance through rope wick applicators. In: *Proceedings 1981 Annual Meeting Southern Weed Science Society*, Dallas, 301-304.

ZIMDAHL RL (1999) Fundamentals of Weed Science. Academic Press, San Diego.

Chapter 3

3 An investigation of factors influencing severity of pasture damage during spot-spraying of herbicides

3.1 Introduction

The increase in frequency of herbicide resistant biotypes of weeds and the demands to lower herbicide loading of the environment have made it desirable to develop weed management systems that apply herbicides more precisely (Combellack, 1990). Spot-treatment of weeds when their density is low may reduce herbicide use compared to boom-spraying (James et al., 1997). In New Zealand, farmers normally use phenoxy herbicides (e.g. 2,4-D or MCPA) for broadcast application on pastures. However, New Zealand pastures are typically a mixture of both perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) (Kemp et al., 2000) and some of these herbicides are damaging to clover (Matthews, 1965).

Spot herbicide treatment is especially recommended for infestations of scattered plants and for any follow-up work in areas where earlier boom spraying has not achieved a complete kill or where some plants have been missed (Taylor, 1973). Weed species that survive boom-spraying are generally difficult to kill, so farmers need to apply a different spectrum of herbicides that are generally more damaging to at least one of the components of pasture, which need to be applied carefully to target weeds to minimise pasture damage (Matthews et al., 2000). These herbicides, such as metsulfuron, picloram, triclopyr, clopyralid, and dicamba are highly toxic to clovers and some have a long residual life in the soil (Tomlin, 2000). In New Zealand, spot-application of herbicides is traditionally done either with a knapsack sprayer or a hand-held spray gun attached by hose to a pressurised tank of herbicide mounted on a vehicle. Herbicide application with spray guns or knapsack sprayers is often not very precise with significant amounts of chemical being applied to, and killing non-target vegetation around the weed due to the commonly practised strategy of application to run-off.

The resultant bare ground is likely to be colonised by opportunistic weeds of lower or no forage value (McConnaughay & Bazzaz, 1987). Most ecological studies on vegetation dynamics have shown that the species composition is dramatically changed by gap creation and, although gaps become more similar to undamaged areas with time, the recovery process is relatively slow depending on the size and cause of disturbance (Morgan, 1997; King & Grace, 2000; Vandvik, 2004). The colonisation of bare ground and gap filling in pastures follows a series of successions before the sward returns to its original composition (Lavorel et al., 1994; Kotanen, 1997). However, in some situations, the original composition may not be reached without re-sowing some of the pasture species. In well-managed swards, species that colonise gaps primarily as seedlings, become relatively more dependent on gaps for local population persistence (Goldberg, 1987).

The initial colonisation of bare ground is limited by the availability of seed and other propagating material, and hence there is a general tendency for species that are common in the sward to also become the most successful gap colonisers (Reader & Buck, 1991; Bullock et al., 1995). Colonisers developing from seeds are more likely to appear in large rather than small gaps as competition from established species around the large gaps will take longer to impact on the central parts, thereby providing sufficient time for seedling colonisation to occur (Reader & Buck, 1991; Bullock et al., 1995; Rogers & Hartnett, 2001).

The persistence of herbicides in the soil is determined by interactions between the herbicide and the soil including herbicide chemistry, soil properties (e.g. soil organic matter and soil type), meteorological factors (e.g. temperature and rainfall), and other factors such as rate of herbicide application (Helling, 2005). Herbicide persistence is usually expressed as half-life, i.e. the time for dissipation of 50% (DT50) of the applied herbicide from soil; and this varies with climate and soil (Helling, 2005).

The residual life of herbicides in the soil is important in determining the recovery time of pastures. Herbicides break down through either chemical or microbial degradation. The speed of chemical degradation depends on the soil type, organic matter content, soil moisture and temperature. Microbial degradation depends on availability of suitable microorganisms in the soil to break down the herbicide. Both processes are accelerated by optimum soil temperature and moisture (Youngson et al., 1967; Riley & Morrod, 1977; Walker, 1991; Yaduraju, 1994; Pons & Barriuso, 1998).

Little information is available on the time it takes for damaged pasture to recover from spot treatments by herbicides and the influence of gap size on the recovery time. Although some previous spot treatment research has assessed effects on pasture, most of the focus has been on the dosage rates and effectiveness of herbicides in killing target weeds (Taylor, 1973; Martin et al., 1988). Therefore, this experiment was designed to quantify the impact of some of the main spot-spraying treatments on pasture plants that are exposed to herbicide around the target weed. A standard application rate was compared with a 3-fold application to show the impact of over-dosing. The time it took gaps of different sizes to recover from spraying was monitored, to determine the impact of different herbicide rates and correlation between gap sizes and pasture productivity.

3.2 Materials and methods

3.2.1 Study sites

Field experiments were conducted in an established 10-year old perennial ryegrass and white clover pasture at the Moginie Pasture and Crop Research Unit of Massey University, Palmerston North, from December 2004 to September 2005. The area has an average annual rainfall of 960 mm and the average mean daily maximum temperature ranges from 22°C in February to 12°C in July. Table 3.1 shows the mean monthly rainfall and temperature for the trial period.

Table 3.1 Total rainfall (mm) and average maximum temperatures (^{o}C) for the duration of the experiment

Month	*Rainfall*	*Temperature*
December 2004	154.6	18.5
January 2005	68.2	22.2
February 2005	28.4	25.2
March 2005	50.4	22.3
April 2005	52.2	18.3
May 2005	85.4	16.7
June 2005	65.0	13.2
July 2005	87.6	13.9
August 2005	44.4	15.4
September 2005	104.2	17.0

3.2.2 Soils

Soil tests prior to treatment indicated a mean pH of 5.6 ($CaCl_2$). Olsen P was measured at 50.8 µg P/g while the K, Mg, and Ca levels averaged 0.68, 1.22, 5.5 me/100 g. Soil organic matter averaged 5.5% and soil was classified as a Tokomaru silt loam. Plots were fertilised once in November 2004 prior to treatment at 250 kg/ha Crop Master 15 with an N, P, K, S composition of 15.2 - 10 - 10 - 7.7, respectively.

3.2.3 Experimental design

The herbicides assessed and their application rates (grams active ingredient/ha) for low and high rates respectively were: glyphosate (360 & 1080), a triclopyr/picloram mixture (500/250 & 1500/750), clopyralid (600 & 1800), and metsulfuron (30 & 90). The products used were Roundup G II (glyphosate); Tordon Gold (triclopyr/picloram), Versatill (clopyralid) and Escort (metsulfuron). The low doses were applied in a standard spot-spraying application rate of 1000 L/ha, whereas high rates were applied in 3000 L/ha to simulate over-dosing.

Each rate was applied to two different patch sizes to show the effect of gap size on the time it takes for pasture recovery. The circular patches (gaps) were 30 cm diameter (0.07 m^2) and 80 cm diameter (0.5 m^2) for small and large patches respectively. There were two untreated controls (one for each size) and each treatment was replicated six times to give a total of 108 patches. Herbicides were applied to create the patches on 6 and 7 February 2004.

An extra three replicates of treatments with large patches created by clopyralid, metsulfuron, and triclopyr/picloram at both rates as well as the untreated control were prepared to provide samples for a bioassay study to determine the persistence of these herbicides.

Treatments were allocated to patches using a randomised complete block design with six blocks and 18 treatments in each block for the main trial. Blocking was based on the clover content of each patch. The distance between patches was 2.5 m from centre to centre. A plastic label placed vertically at the centre marked each patch.

The size of patches was determined by a series of small experiments whereby water was sprayed on to a concrete floor for the same time it would take to spot spray in the field. The diameter of the sprayed patches was then measured. The volume sprayed was measured by spraying water into a measuring cylinder for similar times as spraying on the floor. The small and large patch size was determined by simulating what happens when the middle of a plant is sprayed for a short time versus full coverage for the large patch. Circular patches were created by surrounding the area to be treated with a ring made from a plastic strip 3 mm thick and 10.5 cm wide. Herbicides were then sprayed within each circular patch using a handheld sprayer to evenly distribute measured volumes of herbicide solution.

3.2.4 Pasture production and composition

The botanical composition (frequency of occurrence of various species) of each patch was measured using point analysis (100 points per big patch and

60 points per small patch). The pasture quantity was estimated using a Grassmaster II pasture capacitance probe meter. Five measurements taken from each patch were averaged to give a single figure. This process was repeated monthly for six months for point analysis and for three months for the pasture probe. Botanical composition was categorised into grass, clover, weed and bare ground. Since the pasture was predominantly perennial ryegrass and white clover, there was no attempt to differentiate these from other species of grass or clover. Prior to treatment, the average composition of the sward was 86.3% grass, 12.6% clover, 0.7% weeds and 0.5% bare ground. The weeds were primarily dock (*Rumex* spp.), catsear (*Hypochoeris radicata* L.), dandelion (*Taraxacum officinale* L.), hawksbeard (*Crepis capillaris* (L.) Wallr.) and hawkbit (*Leontodon taraxacoides* (Vill) Merat).

Although the trial was conducted in grazed pasture, the plots were fenced off to keep livestock out during the trial. The height of the pasture was controlled by mowing the plot to a height of 5 cm. The mowing was done every two to three weeks and the clippings were removed from the plot.

3.2.5 Bioassay

For the extra three replicates of some treatments, three soil cores (2.5 cm diameter, 5 cm depth) were taken randomly from each gap every two weeks. Each soil core was put into a separate 200 cm^3 pot after root fragments were removed from the soil. The pots were 30% filled with vermiculite before the soil was added to reduce the amount of soil required from each gap. Each pot was sown with 35 white clover seeds, and kept in a glasshouse with mean monthly temperatures ranging from a low of 13.9^{o}C in July to a high of 23.3^{o}C in January. Subsurface irrigation kept the pots moist, though this was occasionally supplemented by overhead irrigation. The pots from each batch were randomly located within the glasshouse. Space for new samples was created as the older plants were harvested and weighed.

Germination percentage was recorded for each treatment. The emerged seedlings were examined for stunting of growth, yellowing or discoloration of leaves and stems. A score was assigned weekly to the plants according to the severity of injury symptoms. Herbicide injury scores ranged from 1 to 10, where 1 = dead, 10 = no visible injury. After 5 weeks the seedlings were harvested and their fresh weight recorded. Soil samples were taken from the field fortnightly until bioassay results showed no difference between the treatments and the untreated control.

3.2.6 Data analysis

Natural log of the response variables was used to satisfy model assumptions of normality. Because there were a number of zero values in the data, 1.5 was added to every observation to allow the use of log transformation as shown by the following formula: Log (Y+1.5) where Y denotes the response variable. The log transformations made the variance of the measured variable constant across treatments simplifying models used for data analysis. SAS version 9.1 (SAS Institute, 2004) was used for all statistical analyses and significance was set at $P<0.05$ for all comparisons. The following Anova models were used in all experiments. Y (response variable) = A B for two way Anova (main effects) and Y = A|B for two-way factorial with interaction. In situations where blocking was used, the following model was used Y = Block A B A*B. Untransformed means for species composition of patches are shown in the results.

3.3 Results

3.3.1 Untreated control

The clover content of untreated plots more than doubled in January and February relative to December. However, there was a sharp decline in the clover content from March. By September there was virtually no clover in any of the patches, both treated and untreated. Fig 3.1 shows the change in the botanical composition of untreated patches over the duration of the trial.

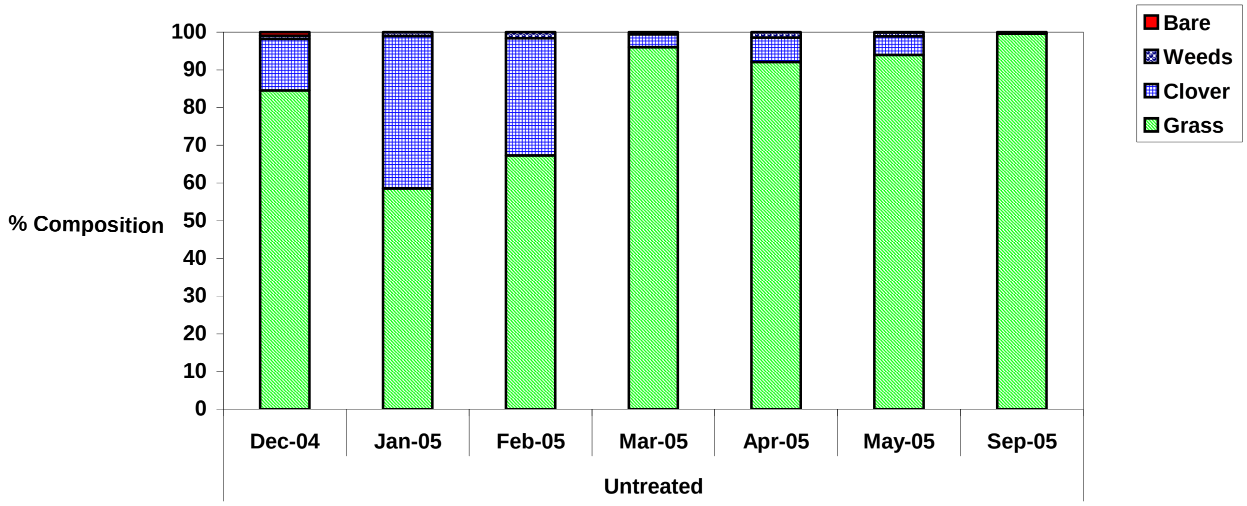
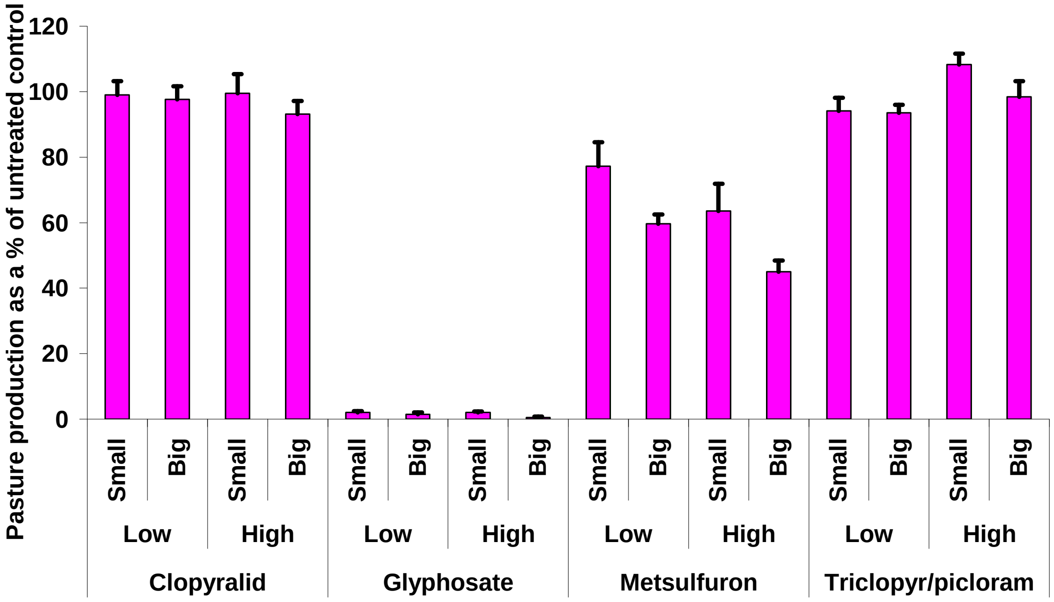


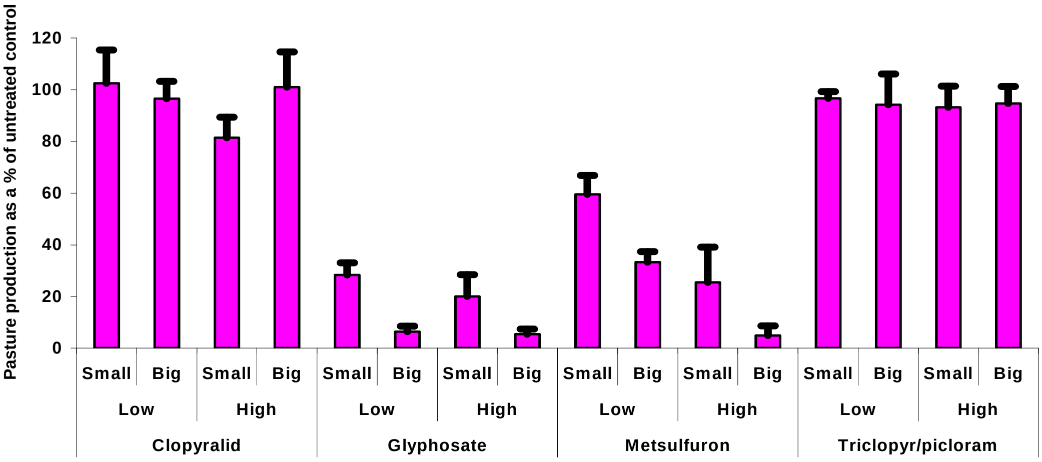
Fig 3.1 **Botanical composition of untreated patches over time**

Based on capacitance readings (pre-mowing), pasture production of the untreated patches was not different from triclopyr/picloram and clopyralid but significantly different from glyphosate and metsulfuron-treated patches (Fig 3.2).

January



February



March

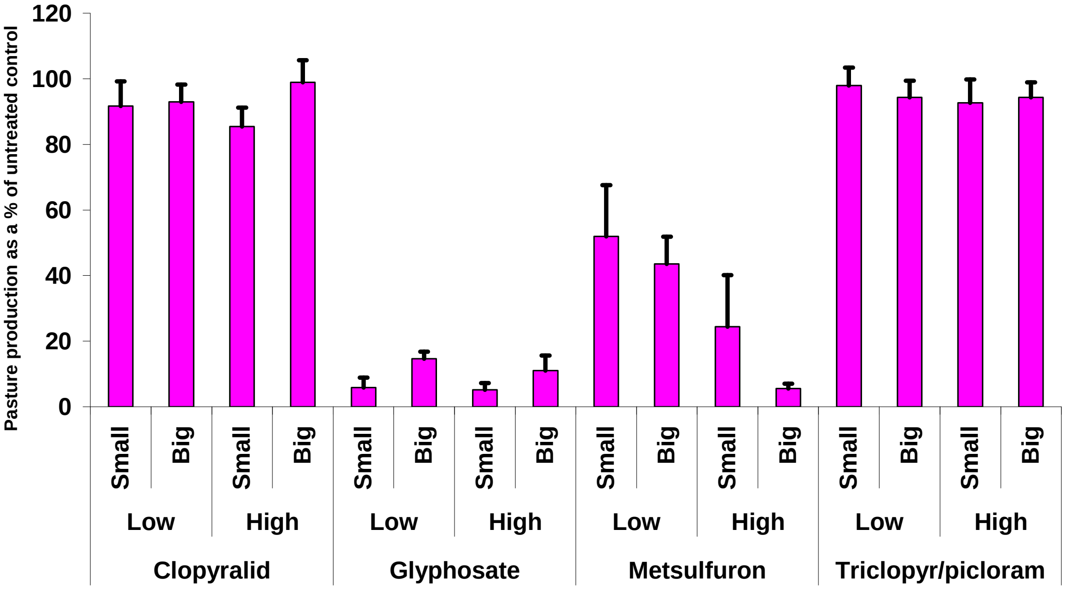
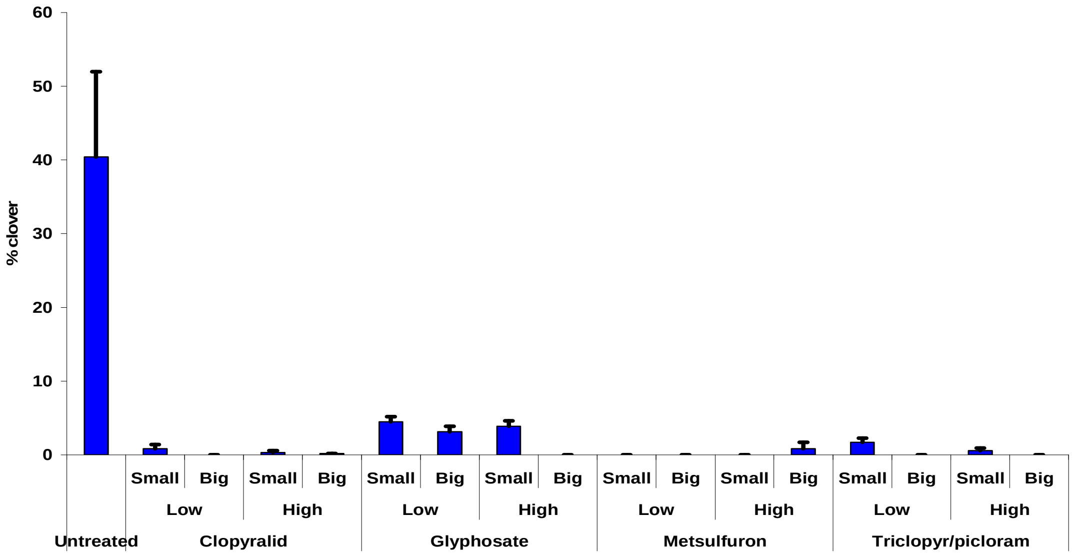


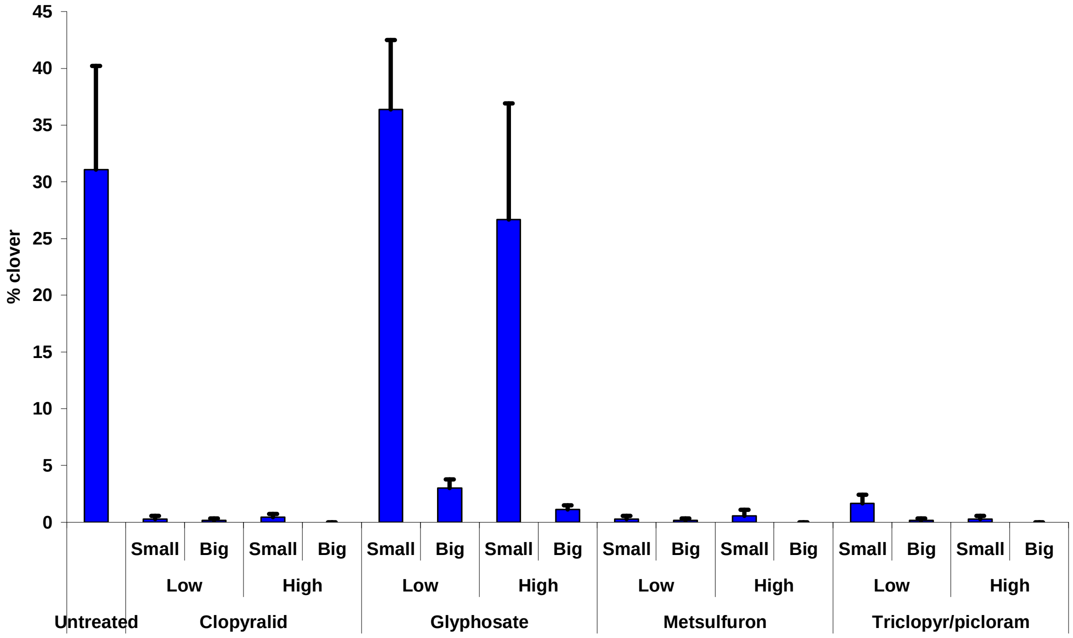
Fig 3.2 Pasture production as a percentage of untreated control for the first 3 months after application (mean of 6 patches). Vertical bars represent standard errors of the mean values.

The clover content of untreated patches differed significantly from all herbicides (Fig 3.3). However, the effect of glyphote was to reduce the clover content initially (January), was equivalent to untreated control (February) and from March onwards exceeded the untreated control.

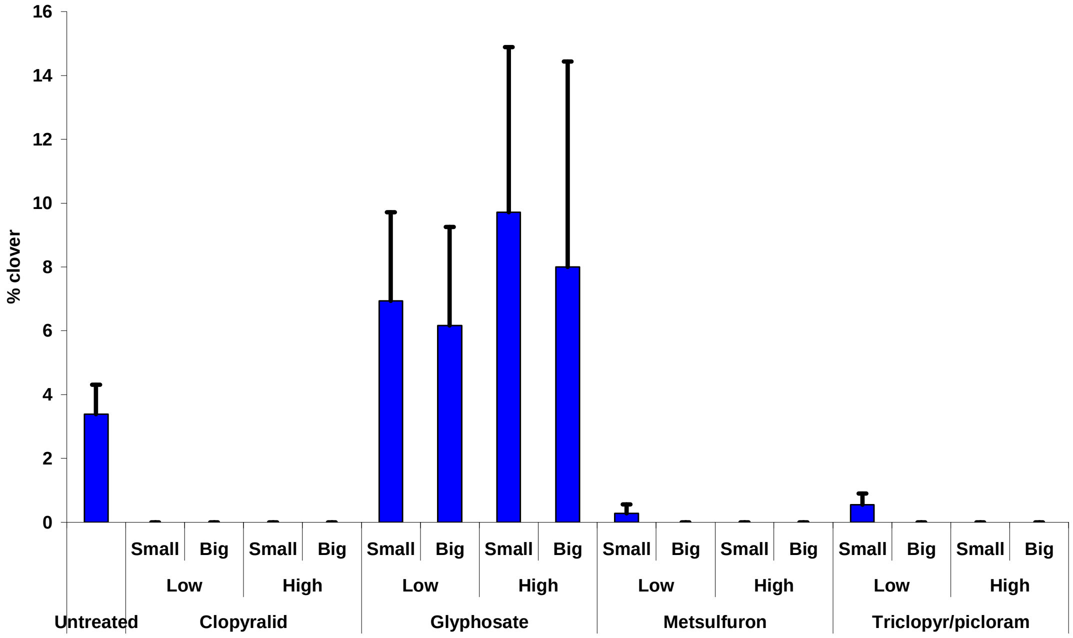
January



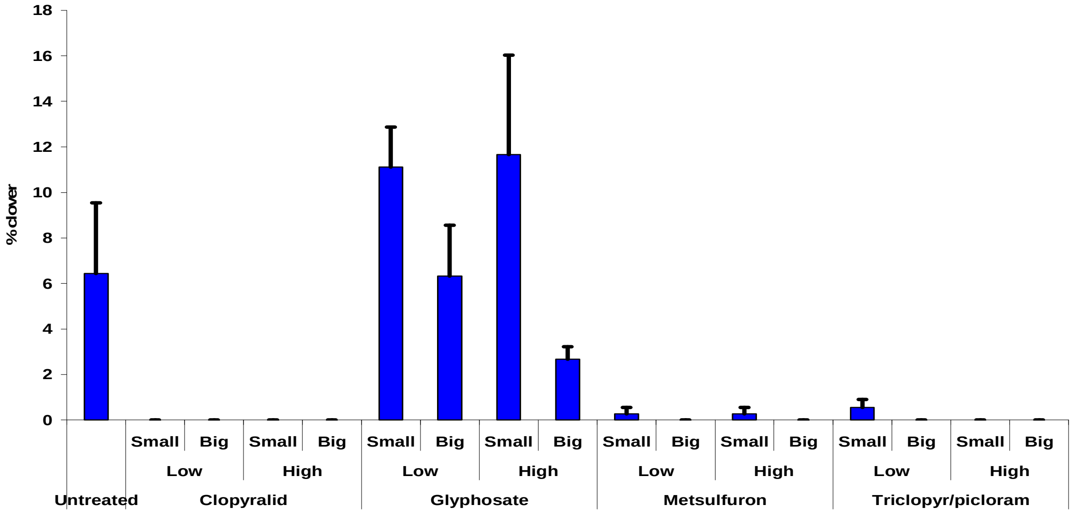
February



March


% clover
16
14
12
10
8
6
4
2
0
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Low
High
Low
High
Low
High
Low
High
Untreated
Clopyralid
Glyphosate
Metsulfuron
Triclopyr/picloram

April


% clover
18
16
14
12
10
8
6
4
2
0
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Small
Big
Low
High
Low
High
Low
High
Low
High
Untreated
Clopyralid
Glyphosate
Metsulfuron
Triclopyr/picloram

May

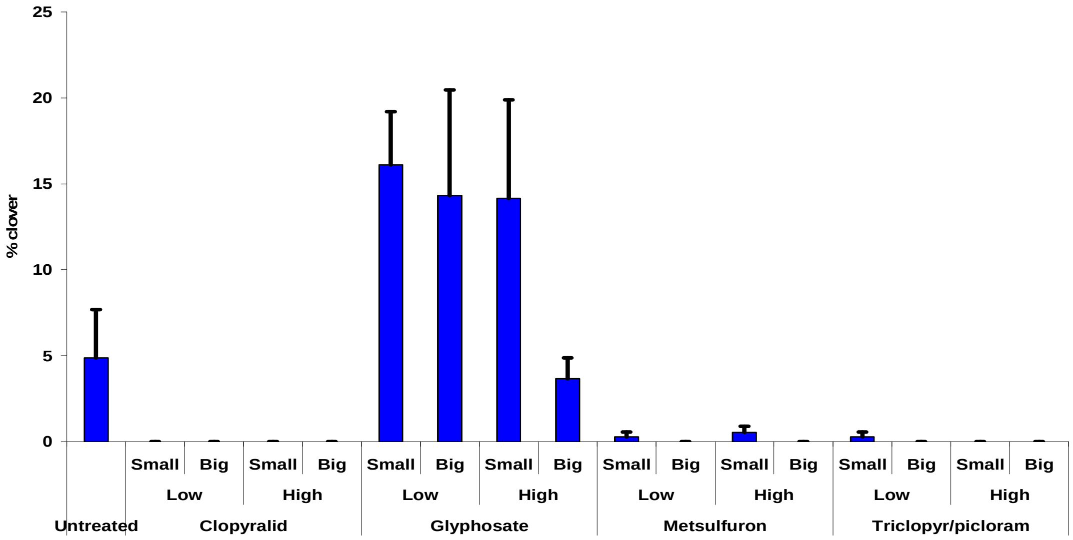


Fig 3.3 Clover content of patches for January to May (mean of 6 patches). Vertical bars represent standard errors of the mean values.

3.3.2 Metsulfuron

Metsulfuron was highly damaging to pasture leading to removal of clovers and suppression of ryegrass. The clover content of the patches was less than 1% for all metsulfuron-treated patches from January until the end of the trial with no clover at all in most patches (Fig. 3.4). The clover content in patches treated with higher rates was similar to those treated with a lower rate. The initial size of the patch did not affect the proportion of clover in the metsulfuron-treated patches.

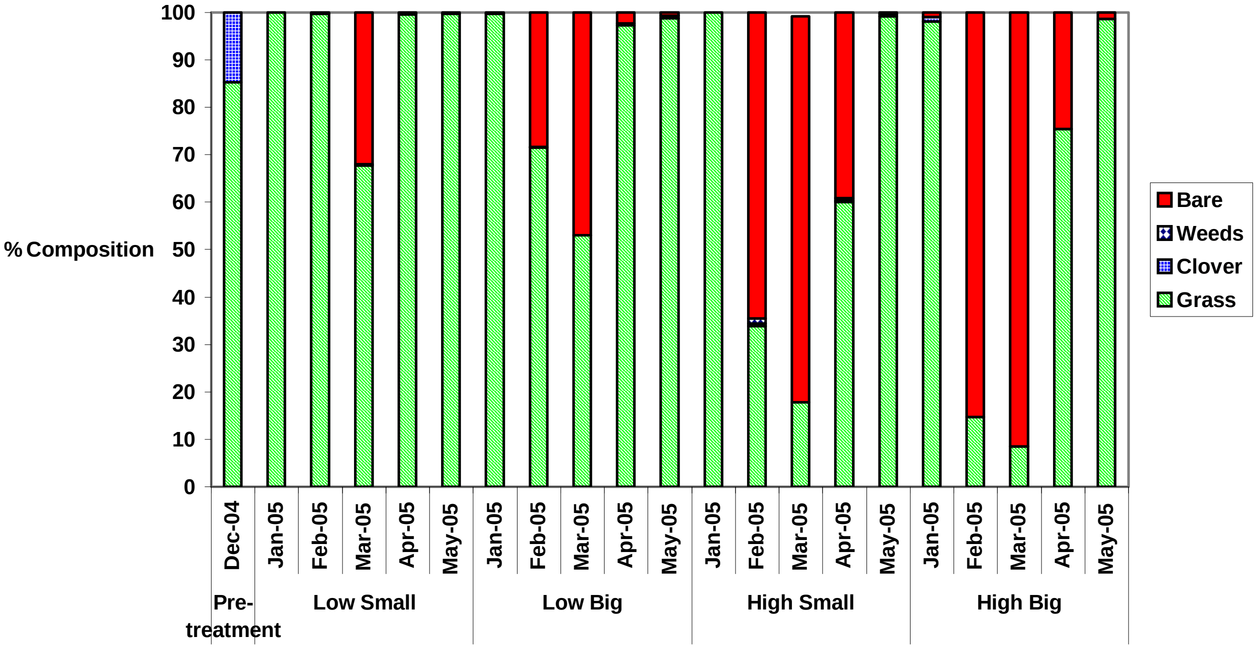


Fig 3.4 Botanical composition over time (mean of six replicates) of small and large patches treated on 6 Dec 2004 with low or high rates of metsulfuron.

Pasture production was reduced to as low as 15% of untreated control for the high rate and 47% for the low rate (Fig 3.2). The patches treated with the higher rate were only fully re-colonised by grass five months after treatment. However, there was no clover or weeds colonising gaps treated with metsulfuron. Some grass species were more tolerant to metsulfuron than others with ryegrass being more susceptible than browntop (*Agrostis capillaris* L.).

The initial patch size had an effect on the recovery and re-colonisation of metsulfuron-treated plots. The large metsulfuron-treated patches took longer to recover and had significantly more bare ground than smaller patches up to March 2005, 3 months after treatment (*P*<0.05). There were no weeds re-colonising any of the patches treated with metsulfuron up to 9 months after treatment, possibly due to the residual activity of the herbicide.

3.3.3 Glyphosate

The effect of glyphosate was to initially reduce the grass and clover content of the patches. However, the smaller patches quickly recovered and had more clover than untreated control for the months of March to May (Fig 3.3). Glyphosate was found to be highly damaging to pasture. Pasture production was reduced to as little as 1.2 % of the untreated control. All the glyphosate–treated gaps had more than 94% bare ground within a month of treatment (Fig 3.5). The bare ground was rapidly colonised by weeds in the large patches while weed colonisation was a bit slower in the small patches (Fig 3.5).

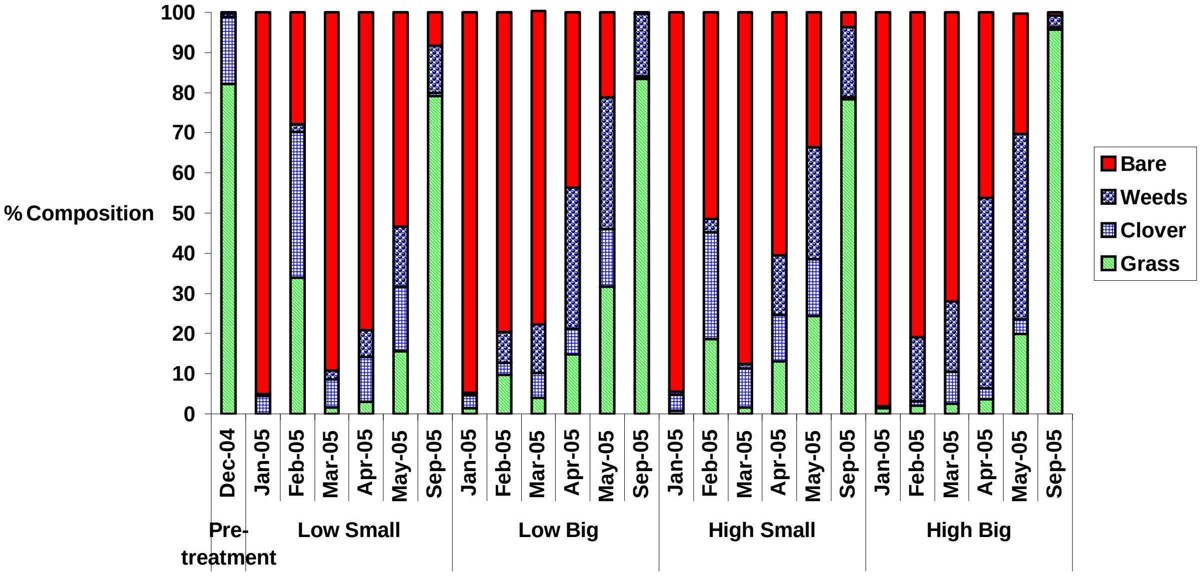


Fig 3.5 Botanical composition over time (mean of six replicates) of small and big patches treated on 7 Dec 2004 with low or high rates of glyphosate.

The most common weed species to emerge in the bare patches were Scotch thistle (*Cirsium vulgare* (Savi) Ten.), black nightshade (*Solanum nigrum* L.), dock (*Rumex* spp.), turf speedwell (*Veronica serpyllifolia* L.), pennyroyal (*Mentha pulegium* L.), catsear, dandelion, hawksbeard, hawkbit, annual mouse ear chickweed (*Cerastium glomeratum* (Thuill.), mouse-ear chickweed (*C. fontanum* (Baumg.)) and chickweed (*Stellaria media* L (Vill)). The weeds were most common in larger gaps, the smaller gaps were rapidly colonised by spreading clover stolons.

The rate of application and the initial patch size had an influence on the clover, weed and proportion of bare ground in the treated patches. The rate of application had an effect on the clover content for 2 months up to February. When the low rate was applied, there was significantly more clover than when the high rate was applied ($P<0.05$).

The initial patch size had an effect on the clover content of glyphosate-treated plots up to April ($P=0.003$), four months after treatment with the smaller patches having a higher clover content than the larger ones. However, the patch size had no effect for the month of March (3 months after treatment). This anomaly could be due to the effect of drought when there was a strong senescence of clover. The patch size had an effect on the weed density of plots with large gaps having a significant amount of weeds up to May 2005, five months after treatment ($P<0.05$).

The initial patch size had an effect on the recovery and re-colonisation of glyphosate-treated plots. The large patches had a significantly higher proportion of bare ground than small patches only for the month of February, 2 months after treatment ($P<0.01$). However, the higher weed density in large patches meant that the proportion of bare ground was significantly reduced. By September, the proportion of bare ground (relative to the initial size) of smaller patches had increased from previous months. The smaller gaps were initially colonised rapidly by spreading clover stolons, but when the clover in the whole trial suddenly disappeared due to arrival of Clover Root Weevil in the area, the smaller patches were left exposed with very little clover having germinated in the plots. The rapid re-colonisation of smaller patches by spreading stolons also meant that very few weeds or grasses successfully established in these patches.

3.3.4 *Clopyralid and triclopyr/picloram*

Clopyralid and triclopyr/picloram had a similar effect on vegetation. The two herbicides completely removed clover from most plots, and throughout the 9 months trial period, the clover content never reached above 1.7% for any treatment (Fig 3.6 & Fig 3.7). However, triclopyr/picloram and clopyralid had no effect on pasture production as measured by the capacitance probe (Fig 3.2).

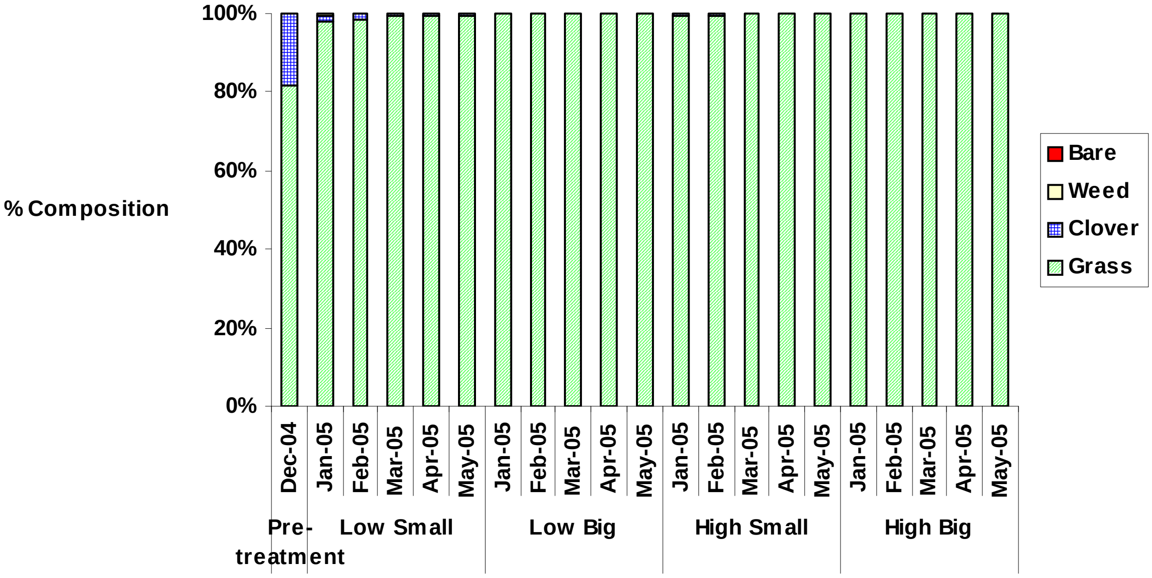


Fig 3.6 Botanical composition over time (mean of six replicates) of small and big patches treated on 6 Dec 2004 with low or high rates of triclopyr/picloram

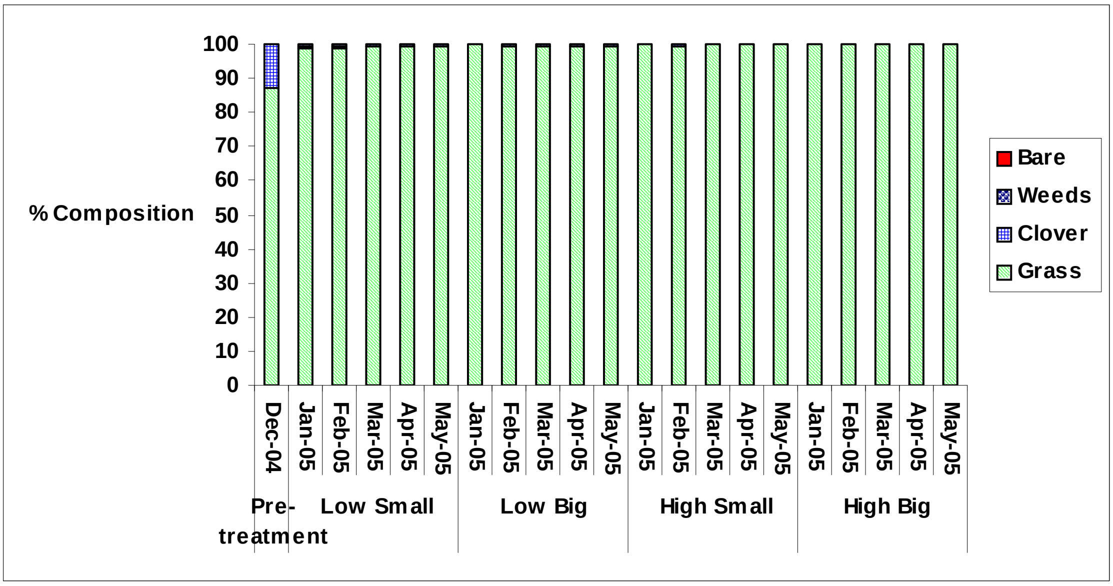


Fig 3.7 Botanical composition over time (mean of six replicates) of small and big patches treated on 6 Dec 2004 with low or high rates of clopyralid.

There were also virtually no weeds in these patches with grass the only vegetation present. This was because, unlike with glyphosate-treated plots, there was no bare ground formed for opportunistic weeds to colonise.

The initial gap size or rate of application of the two herbicides did not have an effect on the clover content of the plots as the lower rate was sufficient enough to remove clover completely.

3.3.5 Bioassay

3.3.5.1 Metsulfuron

The residual life of metsulfuron was shown to be the least of all the herbicides tested, ranging from between 21-42 days (Fig 3.8). Samples taken after 42 days show that the clover yield from plots treated with the standard rate (low) of metsulfuron was 20% more than the untreated control while the yield from the high rate was not different from the untreated control. The herbage yield from metsulfuron treatments for the bioassays was consistently greater than the untreated control for the period between 42 days and 175 days after treatment.

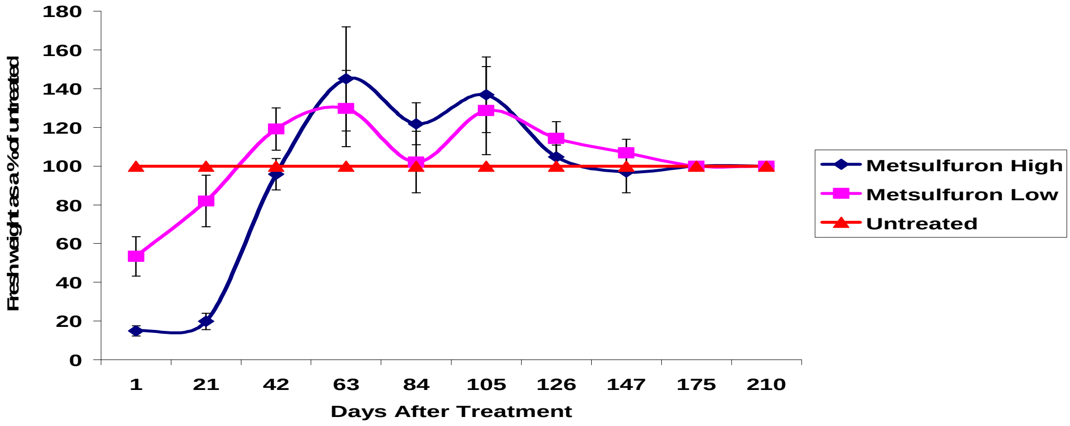


Fig 3.8 The effect of two rates of metsulfuron on clover seedlings grown in the treated soil at different times after application (Vertical bars refer to standard errors of the mean of nine samples with three samples from each patch).

3.3.5.2 Clopyralid

Clopyralid had a long residual life in the soil with both rates causing significant depression of clover seedling growth for 126 days (18 weeks) after treatment (Fig 3.9).

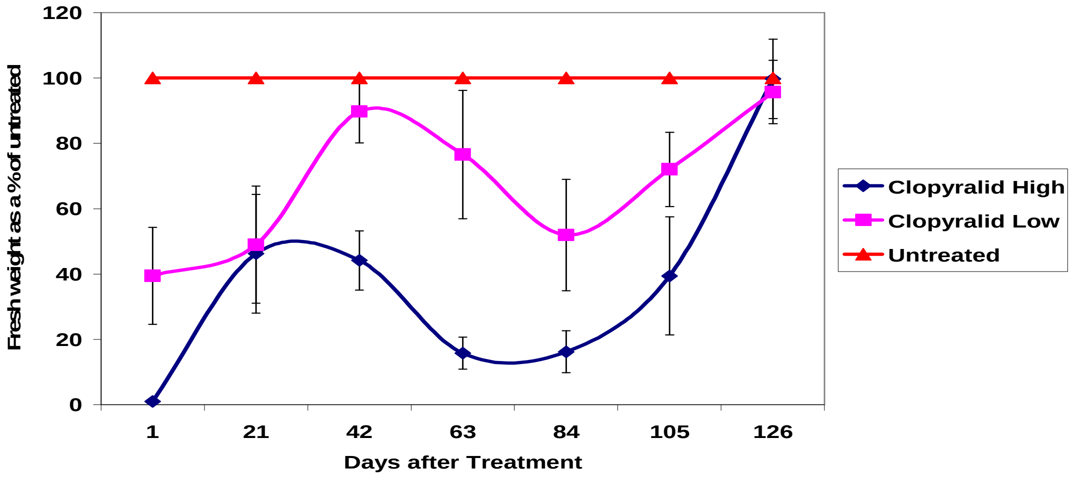


Fig 3.9 The effect of two rates of clopyralid on clover seedlings grown in the treated soil at different times after application (Vertical bars refer to standard errors of the mean of nine samples with three samples from each patch).

The higher rate of clopyralid caused a residual effect in the soil 12 weeks after treatment to suppress clover seedling growth by over 80%. However, there was a sharp increase in production after 12 weeks with the yield levels reaching those of untreated plants at 126 days after treatment.

3.3.5.3 Triclopyr/picloram

Residues of triclopyr/picloram treatment persisted longer than the other herbicides (Fig 3.10). Clover growth for the high rate was still below 10% of untreated control up to 105 days (15 weeks) after treatment with the clover yield equalling that of untreated control 210 days (30 weeks) after treatment. The clover yield for the low rate took up to 147 days (21 weeks) to reach that of untreated control.

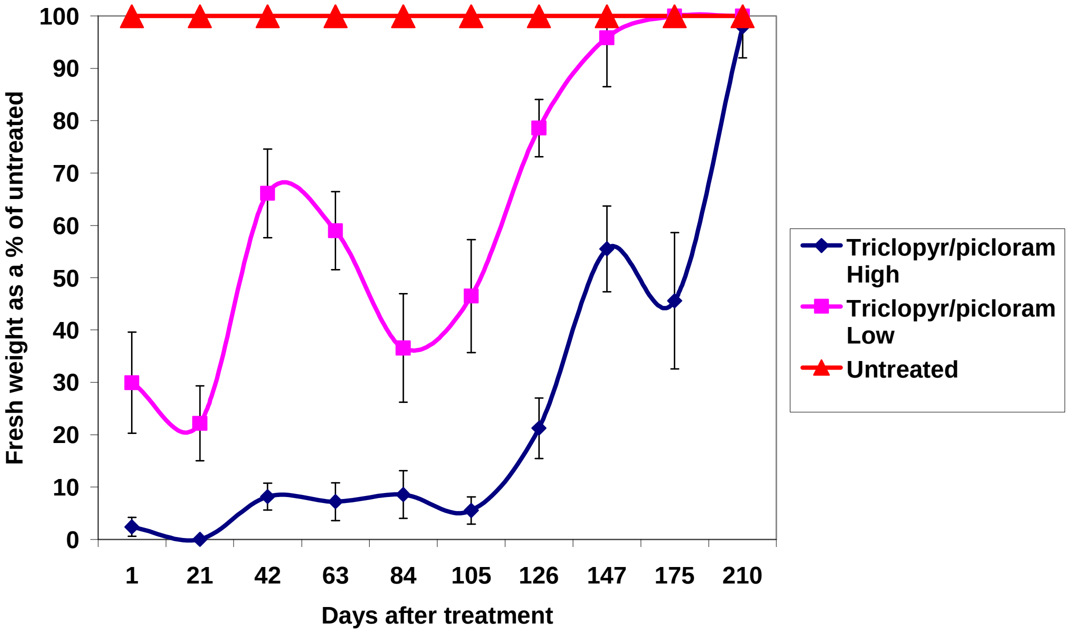


Fig 3.10 The effect of two rates of triclopyr/picloram on clover seedlings grown in the treated soil at different times after application (Vertical bars refer to standard errors of the mean of nine samples with three samples from each patch).

3.4 Discussion

The extent of pasture damage during spot spraying is determined by a variety of factors including the type of herbicide, the size of off-target area that receives herbicides, rate of application and application method. The results of this study have shown that the higher rates persist longer in the soil and this impacts negatively on clover re-establishment. In addition, the higher rates are much more damaging to pasture than lower rates. Bigger patches have also been shown to take longer to recover from damage than the smaller patches. Spot-treatment of mature weeds to runoff as is currently practised means that a higher rate of herbicides is likely to be used and that the area around the weeds that is damaged by the herbicide is likely to be bigger.

Metsulfuron at both rates was shown to be highly damaging to clover. However, the lower rate was not as damaging to the ryegrass as the high rate. Removal of clover by metsulfuron confirmed earlier research by James et al. (1999). Field observations showed that most of the grass that survived metsulfuron treatment was predominantly browntop (*Agrostis capillaris* L.) confirming earlier research by Popay et al. (1985) that showed browntop's high level of tolerance to metsulfuron. The initial patch size as well as the herbicide rate did not affect the proportion of clover in the metsulfuron-treated patches. This was in sharp contrast to glyphosate-treated patches where clover stolons invaded from beyond the edge of the patch and almost completely covered the smaller gaps. Also, a small number of stolons survived the low rate of glyphosate and started to re-grow in situ. For metsulfuron, there was no invasion of clover stolons, probably because there was lateral movement of residues out of the treated patches. There was also no clover that survived the low rate of metsulfuron unlike in the glyphosate treatment. The clover content in patches treated with metsulfuron remained low throughout the experiment. There was no difference in the clover content between both rates of metsulfuron indicating that the low rate was sufficient to remove all the clover thereby masking any rate effect.

In contrast, herbicides such as glyphosate that create bare ground and have no residual soil activity are likely to increase the chances of opportunistic weeds colonising the damaged patches. Weeds with large seed banks have a higher chance of successful re-colonisation. Although white clover is known to have a large seed bank in the soil (Tracy & Sanderson, 2000), its re-colonisation of bare ground was not as successful as that of weeds. The results of this study show that glyphosate-treated large patches generally take longer to recover from herbicide damage than the smaller patches. It is therefore important to minimise the amount of herbicide that hits the area surrounding the weed when spot spraying. The higher rate of glyphosate was also more damaging to clover and this increased the risks of opportunistic weeds as well as increasing the cost of the herbicide.

Unlike glyphosate and metsulfuron, clopyralid and triclopyr/picloram had a much longer residual life in the soil, especially the latter. Although these herbicides do not necessarily open up the pasture due to their non-damaging effect on grass, the loss of legumes will reduce forage quality. Removal of clover from a predominantly ryegrass/clover sward reduces the diversity of the sward and reduces pasture resilience in the face of drought or other disturbances (Dodd et al., 2004). The beneficial effects of clover in supporting the nitrogen supply to pastures through nitrogen-fixation and its provision of quality livestock feed has been well documented (Tillman, 1998; Eerens & Ryan, 2000; Brock & Hay, 2001; Ledgard et al., 2001).

Persistence of clopyralid under field conditions has been reported to last up to 14 months depending on soil type, climate, and other factors (Pik et al., 1977; Tanphiphat & Burrill, 1987; Cox, 1998). The rate of degradation of clopyralid is known to be correlated to the quantity of microbes in the soil (Baloch & Grant, 1991). Research elsewhere has shown that soils with higher biomass degraded clopyralid faster than those with lower microbial biomass. Temperature, soil moisture and initial clopyralid concentration all influence the rate of degradation of the herbicide. Overall, higher temperature and higher soil moistures accelerate degradation of clopyralid. Lower initial clopyralid concentration also means that residues disappear from the soil faster (Baloch

& Grant, 1991; Riaz et al., 2003). Herbicide breakdown for picloram has also been shown to be proportional to the initial herbicide concentration (Altom & Stritzke, 1973).

The higher rate of metsulfuron did not necessarily bring increased benefits to weed control. On the contrary, the residues from higher rates remained longer in the soil thereby preventing successful re-colonisation by desirable species such as clover. Besides damage to pasture, these high rates are costly to the farmers especially when higher rates do not necessarily lead to improved weed control. The lower glyphosate rate was not as damaging to clover as the high rate. This result is not surprising since low rates of glyphosate have been known to increase the clover content of swards (Casey et al., 2000).

Although the total area damaged from spot-spraying is small relative to the total area not sprayed, it is the emergence of opportunistic weeds with the potential to release seed and add to the seed bank that will be detrimental to the overall weed management programme in the long term.

For the bioassay experiment, clover yield from metsulfuron-treated soil was higher than the untreated control from six weeks and nine weeks after treatment with the low and high rate, respectively. This was presumably due to hormesis whereby toxic substances at sub-lethal doses have a stimulatory effect on plant growth (Wiedman & Appleby, 1972; Duke et al., 2006). A study by Cedergreen et al. (2005) has shown a stimulatory effect on leaf length of barley exposed to metsulfuron herbicide. Various hypotheses have been proposed to explain the concept of hormesis including compensatory response to stress from a chemical (Wiedman & Appleby, 1972), and the possible effect of low doses on plant hormones (Allender, 1997).

Although bioassay studies showed herbicide residues fall to safe levels relatively quickly for metsulfuron, any clover seedlings emerging in the patches were likely to be killed due to the residual activity of the herbicide. Also, seedlings from other weed species could germinate before the clover. Several factors determine the persistence of a herbicide in soils. The residual activity of metsulfuron has been known to be higher in soils that are alkaline, and lower in acidic soils (James et al., 2004). Research has shown that the half-life of metsulfuron can increase exponentially with increase in pH (Sarmah et al., 1998, 1999, Sarmah et al., 2000). The relatively low pH of the soil (5.6) in the experiment would have favoured faster decomposition of the herbicide as acid hydrolysis is known to be a major degradation pathway for sulfonylurea urea herbicides (Sarmah et al., 1998). However, the pH of the soil at the site was typical of New Zealand pastoral soils (Wheeler et al., 2004).

Higher temperature could also have sped up the breakdown of the herbicide (Blair & Martin, 1988). However, despite the damage to both ryegrass and white clover, broadleaf weeds were completely removed from metsulfuron-treated patches. This makes metsulfuron an effective herbicide whose benefits could be fully realised if the off-target damage could be minimised.

There was a sharp increase in the clover content of untreated plots and some glyphosate treatments over the summer months. The increase in clover content could have been due to the high summer temperatures (Table 3.1) that promote more active clover growth at the expense of ryegrass that prefers cooler temperatures (Kemp et al., 2000). Mowing could also have significantly increased clover content of untreated control plots in the first few months of the trial as would be expected when grass dominance is removed (Seguin et al., 2001).

The disappearance of clover from untreated patches 3 months into the trial probably masked some of the effects of the herbicides. There are several possible reasons as to why there was a sharp decline in clover. There were signs of clover root weevil (*Sitona lepidus* Gyll.) damage on clover. The presence of nematodes, other insect species, and falling temperatures could also have been responsible for the loss of clover as could be more favourable conditions for grass growth because of high levels of nitrogen fixation by clover-dominant summer pastures. The emergence of new autumn grass growth tends to reduce the proportion of clover in the sward.

3.5 Future Research

There is a need to focus research on ways of using optimum rates of herbicide as well as minimising the non-target herbicide spray area. This can be done by choosing an application method that minimises risks of harming non-target plants such spraying the herbicide in the middle of the target plant instead of full plant coverage to run-off. In order to restrict the herbicide application to the smallest possible area, application equipment should be tailor-made to target herbicides to the centre of rosettes. A study to investigate the technique to apply herbicides just to the centre of weeds is further discussed in Chapter 4.

3.6 Conclusions

Glyphosate was extremely damaging to both clover and ryegrass. However, this herbicide can be used for spot spraying if precision of application is such that only the target weed receives the herbicide. Over-application of herbicides should be avoided as higher rates are more damaging and increase the residual life of herbicides in soils making re-establishment of clovers difficult.

3.7 References

ALLENDER WJ (1997) Effect of trifluoperazine and verapamil on herbicide stimulated growth of cotton. *Journal of Plant Nutrition* **20**, 69-80.

ALTOM JD & STRITZKE JF (1973) Degradation of dicamba, picloram and four phenoxy herbicides in soils. *Weed Science* **21**, 556-560.

BALOCH RI & GRANT RK (1991) The investigation of degradation and metabolism of clopyralid in two standard and three agricultural soils. *Monograph - British Crop Protection Council*, 101-108.

BLAIR AM & MARTIN TD (1988) A review of the activity, fate and mode of action of sulfonylurea herbicides. *Pesticide Science* **22**, 195-219.

BROCK JL & HAY MJM (2001) White clover performance in sown pastures: a biological/ecological perspective. In: *Proceedings of the New Zealand Grassland Association* **63**, 73-83.

BULLOCK JM, CLEAR HILL B, SILVERTOWN J & SUTTON M (1995) Gap colonization as a source of grassland community change: effects of gap size and grazing on the rate and mode of colonization by different species. *Oikos* **72**, 272-283.

CASEY MJ, BROWN C & STEVENS DR (2000) A summary of research into the use of low rates of glyphosate as a pasture management tool. In: *Proceedings of the New Zealand Grassland Association* **62**, 123-128.

CEDERGREEN N, RITZ C & STREIBIG JC (2005) Improved empirical models describing hormesis. *Environmental Toxicology and Chemistry* **24**, 3166-3172.

COMBELLACK JH (1990) Efficient utilisation of herbicides. In: *Proceedings 1990 Australian Weeds Conference,* 552-564.

COX C (1998) Herbicide fact sheet: clopyralid. *Journal of Pesticide Reform* **18**, 15-19.

DODD MB, BARKER DJ & WEDDERBURN ME (2004) Plant diversity effects on herbage production and compositional changes in New Zealand hill country pastures. *Grass and Forage Science* **59**, 29-40.

DUKE SO, CEDERGREEN N, VELINI ED & BELZ RG (2006) Hormesis: is it an important factor in herbicide use and allelopathy? *Outlooks on Pest Management* **17**, 29-33.

EERENS JPJ & RYAN DL (2000) Managing white clover for productive and profitable sheep farming in Southland. In: *Proceedings of the New Zealand Grassland Association* **62**, 137-140.

GOLDBERG DE (1987) Seedling Colonization of Experimental Gaps in 2 Old-Field Communities. *Bulletin of the Torrey Botanical Club* **114**, 139-148.

HELLING CS (2005) The science of soil residual herbicides. In: *Soil residual herbicides: science and management* (3-22. Canadian Weed Science Society, Sainte-Anne-de-Bellevue Canada.

JAMES TK, RAHMAN A & CORNWELL MJ (1999) Pasture tolerance to the herbicide metsulfuron-methyl. In: *Proceedings 1999 New Zealand Plant Protection Conference* **52**, Auckland, New Zealand, 240-244.

JAMES TK, RAHMAN A & JONG PD (1997) Flazasulfuron for control of ragwort (*Senecio jacobaea*) in pasture. In: *Proceedings 1997 New Zealand Plant Protection Conference,* Lincoln University, Canterbury, New Zealand, 477-481.

JAMES TK, RAHMAN A, MELLSOP JM & TROLOVE M (2004) Effect of rainfall on the movement and persistence of metsulfuron-methyl and clopyralid applied to pasture. In: *Proceedings 2004 New Zealand Plant Protection Conference*, Hamilton, New Zealand, 271-276.

KEMP PD, MATTHEW C & LUCAS RJ (2000) Pasture species and cultivars. In: *New Zealand pasture and crop science* (eds J White & J Hodgson), 84-99. Oxford University Press, Melbourne.

KING SE & GRACE JB (2000) The effects of gap size and disturbance type on invasion of wet pine savanna by cogongrass, *Imperata cylindrica* (Poaceae). *American Journal of Botany* **87**, 1279-1286.

KOTANEN PM (1997) Effects of gap area and shape on re-colonisation by grassland plants with differing reproductive strategies. *Canadian Journal of Botany-Revue Canadienne De Botanique* **75**, 352-361.

LAVOREL S, LEPART J, DEBUSSCHE M, LEBRETON JD & BEFFY JL (1994) Small-Scale Disturbances and the Maintenance of Species-Diversity in Mediterranean Old Fields. *Oikos* **70**, 455-473.

LEDGARD SF, SPROSEN MS, PENNO JW & RAJENDRAM GS (2001) Nitrogen fixation by white clover in pastures grazed by dairy cows: temporal variation and effects of nitrogen fertilization. *Plant and Soil* **229**, 177-187.

MARTIN P, THOMPSON A & RAHMAN A (1988) Spot treatment of ragwort and nodding thistle with DPX-L5300. In: *Proceedings 1988 New Zealand Weed and Pest Control Conference,* Auckland, New Zealand, 223-225.

MATTHEWS LJ (1965) Tolerance of clovers to herbicides. In: *Proceedings 1965 New Zealand Weed and Pest Control Conference,* Hamilton, New Zealand, 37-41.

MATTHEWS PNP, HARRINGTON KC & HAMPTON JG (2000) Management of grazing systems. In: *New Zealand pasture and crop science* (eds J White & J Hodgson), 153-174. Oxford University Press, Melbourne.

MCCONNAUGHAY KDM & BAZZAZ FA (1987) The relationship between gap size and performance of several colonizing annuals. *Ecology* **68**, 411-416.

MORGAN JW (1997) The effect of grassland gap size on establishment, growth and flowering of the endangered *Rutidosis leptorrhynchoides* (Asteraceae). *Journal of Applied Ecology* **34**, 566-576.

PIK AJ, PEAKE E, STROSHER MT & HODGSON GW (1977) Fate of 3,6-dichloropicolinic acid in soils. *Journal of Agricultural and Food Chemistry* **25**, 1054-1061.

PONS N & BARRIUSO E (1998) Fate of metsulfuron-methyl in soils in relation to pedo-climatic conditions. *Pesticide Science* **53**, 311-323.

POPAY AI, CORNWELL MJ & RAHMAN A (1985) Effects of metsulfuron-methyl on pasture. In: *Proceedings 1985 New Zealand Weed and Pest Control Conference,* Rotorua, New Zealand, 102-105.

READER RJ & BUCK J (1991) Control of Seedling Density on Disturbed Ground - Role of Seedling Establishment for Some Mid-successional, Old-Field Species. *Canadian Journal of Botany-Revue Canadienne De Botanique* **69**, 773-777.

RIAZ A, JAMES TK, ANIS R & HOLLAND PT (2003) Dissipation of the herbicide clopyralid in an allophanic soil: laboratory and field studies. *Journal of Environmental Science and Health. Part B, Pesticides, Food Contaminants, and Agricultural Wastes* **38**, 683-695.

RILEY D & MORROD RS (1977) Relative importance of factors influencing the activity of herbicides in soil. In: *Proceedings 1976 British Crop Protection Conference - Weeds. Volume 3.* 971-980.

ROGERS WE & HARTNETT DC (2001) Temporal vegetation dynamics and re-colonisation mechanisms on different-sized soil disturbances in tall grass prairie. *American Journal of Botany* **88**, 1634-1642.

SARMAH AK, KOOKANA RS & ALSTON AM (1998) Fate and behaviour of triasulfuron, metsulfuron-methyl, and chlorsulfuron in the Australian soil environment: a review. *Australian Journal of Agricultural Research* **49**, 775-790.

SARMAH AK, KOOKANA RS & ALSTON AM (1999) Degradation of chlorsulfuron and triasulfuron in alkaline soils under laboratory conditions. *Weed Research (Oxford)* **39**, 83-94.

SARMAH AK, KOOKANA RS, DUFFY MJ, ALSTON AM & HARCH BD (2000) Hydrolysis of triasulfuron, metsulfuron-methyl and chlorsulfuron in alkaline soil and aqueous solutions. *Pest Management Science* **56**, 463-471.

SAS INSTITUTE (2004) SAS version 9.1.

SEGUIN P, PETERSON PR, SHEAFFER CC & SMITH DL (2001) Physical sod suppression as an alternative to herbicide use in pasture renovation with clovers. *Canadian Journal of Plant Science* **81**, 255-263.

TANPHIPHAT K & BURRILL LC (1987) Persistence of clopyralid in soil. In: *Proceedings 1987 Western Society of Weed Science.* **40**, 75.

TAYLOR RL (1973) Control of ragwort. In: *Proceedings 1973 New Zealand Weed and Pest Control Conference*, Auckland, New Zealand, 50-52.

TILLMAN R (1998) Fertiliser nitrogen or clover nitrogen? In: *Proceedings 1998 Ruakura Farmers' Conference,* Waikato, New Zealand, 80-84.

TOMLIN CDS (2000) The Pesticide Manual. In: *A World Compendium*. British Crop Protection Council, Surrey, UK.

TRACY BF & SANDERSON MA (2000) Seed bank diversity in grazing lands of the northeast United States. *Journal of Range Management* **53**, 114-118.

VANDVIK V (2004) Gap dynamics in perennial sub-alpine grasslands: trends and processes change during secondary succession. *Journal of Ecology (Oxford)* **92**, 86-92.

WALKER A (1991) Influence of soil and weather factors on the persistence of soil-applied herbicides. *Applied Plant Science* **5**, 94-98.

WHEELER DM, SPARLING GP & ROBERTS AHC (2004) Trends in some soil test data over a 14-year period in New Zealand. *New Zealand Journal of Agricultural Research* **47**, 155-166.

WIEDMAN SJ & APPLEBY AP (1972) Plant growth stimulation by sub-lethal concentrations of herbicides. *Weed Research* **12**, 65-74.

YADURAJU NT (1994) Influence of soil environmental factors on the efficacy of herbicides. In: *Soil-environment and pesticides.* (265-292). Venus Publishing House, New Delhi India.

YOUNGSON CR, GORING CAI, MEIKLE RW, SCOTT HH & GRIFFITH JD (1967) Factors influencing the decomposition of Tordon herbicide in soils. *Down to Earth* **23**, 3-11.

Chapter 4

4 Effectiveness of concentrating herbicide application to the centre compared to spraying ragwort (*Senecio jacobaea*) and Scotch thistle (*Cirsium vulgare*) rosettes to run-off

4.1 Introduction

Ragwort (*Senecio jacobaea* L.) and Scotch thistle (*Cirsium vulgare* (Savi) Ten.)) are considered two of the most important weeds of pastures in New Zealand (Bourdot & Kelly, 1986; Bourdot et al., 1994; Seefeldt et al., 2005). These weeds are often spot-sprayed if they occur at low densities, but due to the practice of spraying weeds to run-off, pasture plants at or within the drip line may receive a lethal herbicide dose. The bare ground resulting from the demise of the target weed plant and non target pasture plants is likely to be colonised by opportunistic weeds of lower or no forage value (McConnaughay & Bazzaz, 1987).

An earlier study (Chapter 3) has shown that pasture damage from spot spraying and the recovery of damaged patches is influenced by a variety of factors including the size of the non-target area and the rate of application. It is clear that it is prudent to minimise the non-target impacts of herbicides by more precise application to the centre of the target plant as compared to spraying to run-off. Some translocated herbicides have label recommendations for application to the centre of a weed to minimise pasture damage, though at much higher concentrations than when applied over the whole plant (O’Connor, 2004).

Apparently no study has been published that assesses how much more herbicide is required when applying just to the centre of the weed. This study investigated the implications of spraying a more concentrated herbicide to the centre of weeds in order to achieve the same result as spraying a less concentrated solution to run-off. Metsulfuron and triclopyr/picloram are two of the most commonly used herbicides for spot spraying in New Zealand. As shown in Chapter 3, both these herbicides are very damaging to clovers and have a residual soil activity leading to pasture damage (Thompson, 1974; Meeklah & Mitchell, 1984; Popay et al., 1985).

The effectiveness of the two application techniques was compared by treating two weed species (ragwort and Scotch thistle) with a series of herbicide doses to create dose-response curves that could be compared with untreated controls. Herbicide dose-response curves are useful to describe the action of herbicides in plants. Plant responses to various doses of herbicides usually follow a sigmoid curve relationship where the potency is given by the ED_{50} value (Nielsen et al., 2004), which is the dose required to affect plant response by 50% relative to the lower and upper limit. A dose-response curve can be used to quantify differences in relative efficacy of herbicides and to predict the effects likely to occur at various pesticide concentrations below or above the test concentrations (Streibig et al., 1993, Streibig & Green, 1994).

4.2 Materials and methods

4.2.1 Ragwort experiment

Ragwort seeds were sown in cell trays with 18 cm^3 cells on 7 October 2005. The seeds were harvested the previous year and stored in a cold room at 4^0C. After establishing in trays, the seedlings were transplanted into 2000 cm^3 PB3 planter bags on 31 October 2005. The average daily maximum temperature was 18.4^0C and 22.7^0C respectively for the months of November and December 2005 while the mean maximum daily temperature soon after treatment was 20.0^0C and 16.0^0C for April and May 2006, respectively.

The potting mix used consisted of a 4:1 mixture of bark and pumice. For every 100 litres of mix, 50 g agricultural lime, 150 g dolomite, 50 g Osmocote 3-4-month timed-release fertiliser (NPK 16-3.5-9.1+1.2 Mg + trace elements) and 100 g Osmocote 8-9-month timed-release fertiliser (NPK 15-4.8-10.8+1.2 Mg + trace elements) were added.

The plants were grown in a glasshouse for eight weeks before being transferred outside at the Plant Growth Unit of Massey University, Palmerston North. Water was applied to the plants using capillary matting wetted by means of drip hoses, occasionally supplemented by overhead watering.

Herbicides were applied on 11 April 2006 when plants were 26 weeks old with an average diameter of 15 cm. The herbicides used were a mixture of 100 g/litre triclopyr and 50 g/litre picloram as amine salts in the form of a soluble concentrate (Tordon Gold) and metsulfuron in the form of a 200 g/kg water dispersible granule (Answer). Herbicides were applied either to the centre of rosettes (about 5% of leaf area treated) or to the whole rosette using a small hand-held sprayer. The application rate was 5 ml/plant for both treatments.

Six herbicide rates (all applied at 5 ml/plant) and an untreated control were used for each herbicide to obtain dose-response curves. The metsulfuron rate ranged from 5.9 to 188 µg active ingredient (ai) per plant, with the highest rate being equivalent to 25% of the recommended label rate of 2.5 ml/plant of 7.5 g Answer/5L. However, 5 ml/plant was applied and so the rate was adjusted accordingly. The triclopyr/picloram dosage rates ranged from 98/49 to 3120/1560 µg ai per plant with the highest rate being equivalent to 12.5% of the recommended rate of 5 ml/plant of 1:20 dilution for young plants (O’Connor, 2004).

The application rates had been determined in a pre-trial experiment in which plants were sprayed with many rates from ineffective to those causing 100% mortality in order to arrive at optimum rates for the experiment. The dilution rates used in the main experiment were a 2-fold serial dilution in which each treatment was half the concentration of the previous treatment. Five ml of the herbicide was measured into test-tubes from which a small hand held sprayer was used to apply the herbicide to the plants.

The experimental design was a completely randomised block design with a factorial arrangement of multiple herbicide rates and the two application methods replicated 10 times. The plants were assigned to blocks according to size.

Each plant was assigned a herbicide-injury score at regular intervals after treatment, initially weekly and then less regularly later. A score of 1 represented no visual herbicide effect while a score of 10 represented plants with no visual green leaf material. Most ragwort plants appeared to have died as observed by the absence of any green tissue material present at the June 2006 assessment and scoring was stopped. However, by mid-September new shoots had emerged at which point scoring resumed.

4.2.2 Scotch thistle experiment

Scotch thistle seeds were sown in cell trays with 18 cm^3 cells in March 2006. The seeds were harvested from the field at Massey University and sown directly into trays. The seedlings were then transplanted into 2000 cm^3 PB3 planter bags using the same potting mix as described in the ragwort experiment. The plants were grown in a heated glasshouse (mean temperature of 12^{0}C and 14^{0}C in July and August respectively) and water was applied to the plants as earlier described for the ragwort experiment. A Hortplus micro-logger was used to measure air temperature in the glasshouse.

Herbicides were applied on 1 July 2006 when plants were 13 weeks old with an average diameter of 28 cm. Herbicides were applied either to the centre of the rosette (about 5% of leaf area treated) or the whole plant as earlier described. The application rate was 5 ml/plant for both application methods. Two herbicides were assessed: a mixture of 100 g/litre triclopyr and 50 g/litre picloram as an amine salt (Tordon Gold), and 200 g/kg metsulfuron as a methyl ester (Answer).

Eight herbicide rates and an untreated control were used for each herbicide to obtain dose-response curves. The metsulfuron rates ranged from 0.18 to 23.0 µg ai/plant. The highest rate was 3.1% of the recommended label rate of 2.5 ml/plant of 7.5 g Answer/5L. However, we applied 5 ml/plant and adjusted the rate accordingly. The triclopyr/picloram rates ranged from 3.0/1.5 to 391/196 µg ai per plant. The highest rate was 1.6% of the recommended rate of 5 ml/plant of 1:20 for young plants. Rates were selected based on earlier experiments to give a range of sub-lethal effects on plants. Visual assessments of foliar injury symptoms were conducted as for the ragwort experiment.

4.2.3 Statistical analysis

Linear regression on log herbicide concentration versus plant injury scores was performed for both application methods. The slopes of the two regression lines were then compared by using the Student's t-test. P<0.05 was taken as statistically significant. Data are presented as means of injury scores ± standard error of mean (SEM).

4.3 Results

There was no difference in the damage caused to ragwort using the two application methods for either herbicide (Figs 4.1 & 4.2).

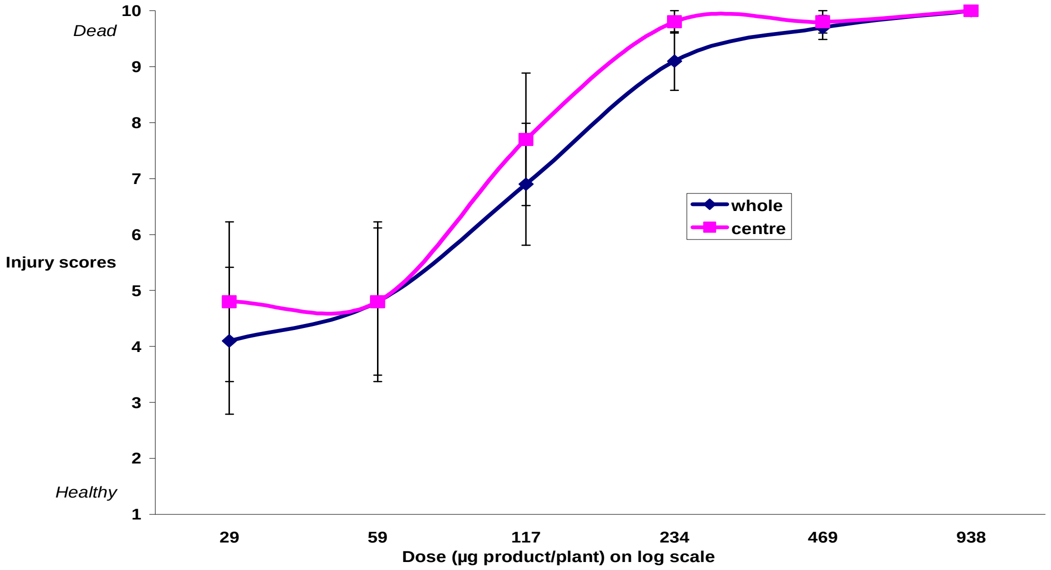


Fig 4.1 The effect (29 weeks after treatment) of applying metsulfuron to either the centre of the rosette or the whole ragwort rosette. (Vertical bars represent SEM, n=10).

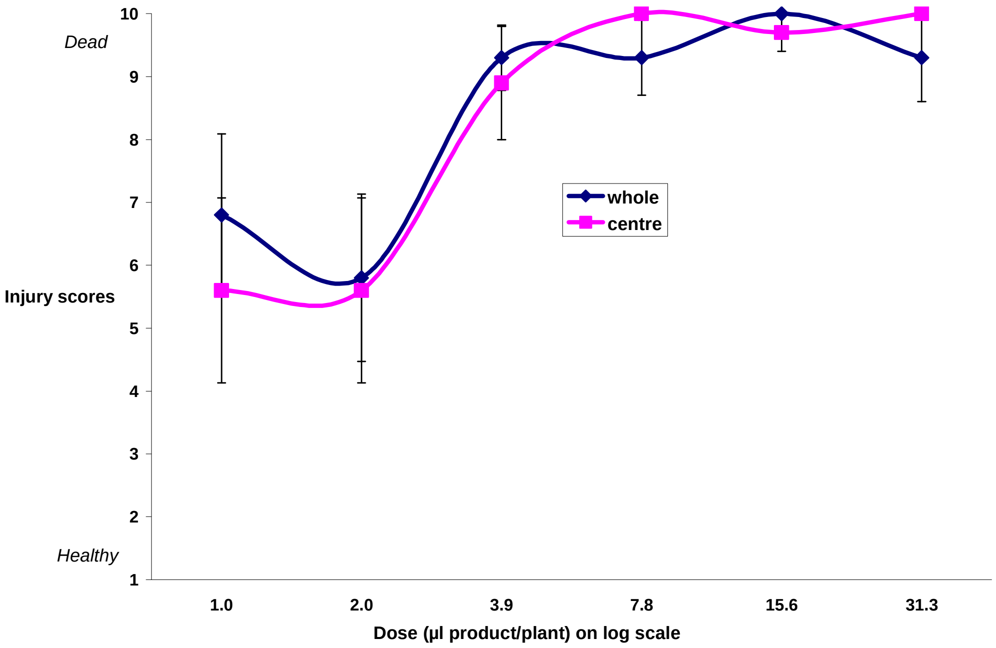


Fig 4.2 The effect (29 weeks after treatment) of applying triclopyr/picloram to either the centre of the rosette or the whole ragwort rosette. (Vertical bars represent SEM, n=10).

There was no difference in the damage caused to Scotch thistle using the two application methods for either metsulfuron or triclopyr/picloram (Figs 4.3 & 4.4). However, at some of the lower concentrations, differences between treatment methods in damage were significant but there was no consistent trend. The highest metsulfuron rate, unlike the highest triclopyr/picloram rate, did not cause mortality to the plants.

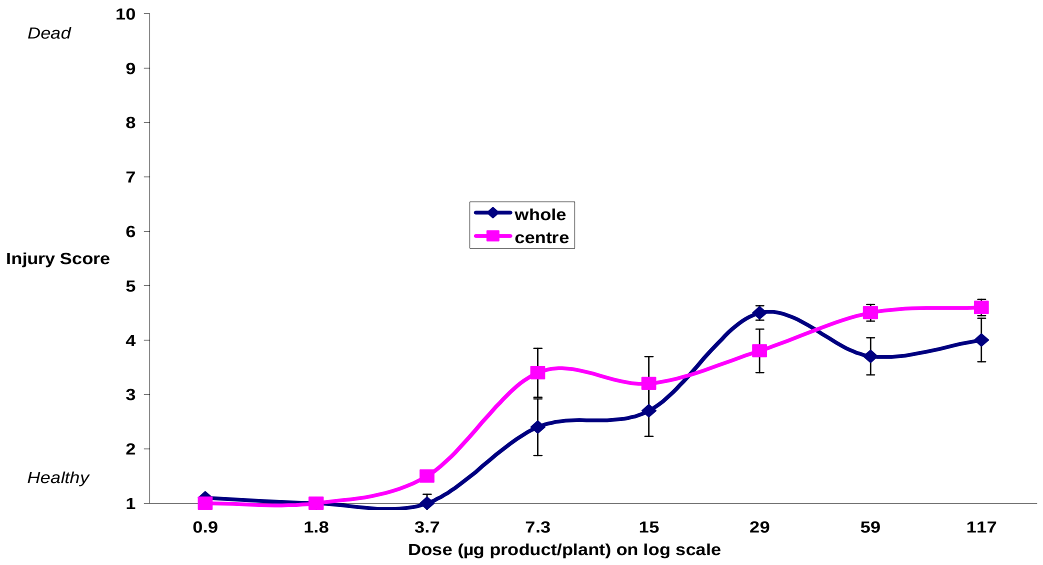


Fig 4.3 The effect (20 weeks after treatment) of applying metsulfuron to either the centre of the rosette or the whole Scotch thistle rosette. (Vertical bars represent SEM, n=10).

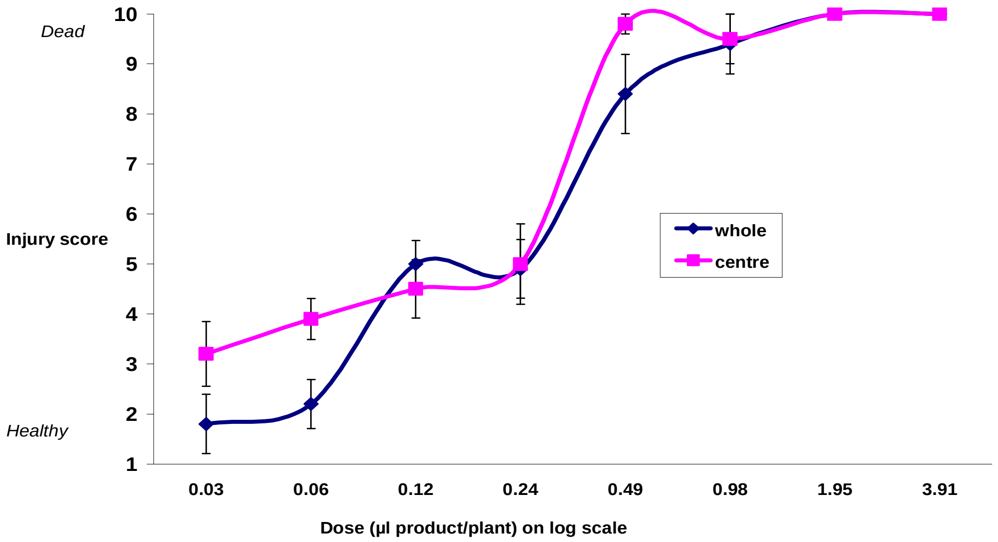


Fig 4.4 The effect (20 weeks after treatment) of applying triclopyr/picloram to either the centre of the rosette or to the whole Scotch thistle rosette. (Vertical bars represent SEM, n=10).

There was an emergence of new shoots from the root fragments in the metsulfuron-treated ragwort plants that had shown total necrosis and had been assigned a score of 10 in June 2006. Most of the regenerated shoots regenerated from plants that had received spray to run-off (Table 4.1). There was more re-generation from plants that received the intermediate dose than those that received the highest rate. The regeneration of plants was not apparent in Scotch thistles.

Table 4.1 The percentage of metsulfuron-treated ragwort plants regenerating from total necrosis 20 weeks after having been classified as totally necrotic

dose rate (µg product/plant)	Full Spray	Centre spray
938	0	0
469	20	10
234	30	10
117	60	20
59	50	20
29	20	0

4.4 Discussion

Current recommendations are to increase herbicide concentrations of metsulfuron by as much as 20 times and by 17 times for triclopyr/picloram when applying only to the centres of rosettes compared to application to run-off (O'Connor, 2004). However, the results suggest that if farmers treat only the centre of plants to avoid pasture damage, higher herbicide application rates may not be necessary assuming that the same volume of spray is applied to the centre of rosettes as would have been sprayed over the entire plant. If lower volumes were used, concentrations would need to increase accordingly, to achieve an equivalent level of active ingredient applied to the plant. Although the total area damaged is small when spraying herbicides to run-off, it is the emergence of opportunistic weeds (Bullock et al., 1995) in the place of the target weed and non target plants that creates a situation whereby undesirable plants are substituted by other undesirable plants over a larger area.

Although application of herbicides only to the centre of the plants would not permit total coverage of the weed by the herbicide, translocated herbicides such as those traditionally used for spot spraying will move within the plant to exert a toxic effect at the target site (Ashton & Crafts, 1981; Anderson, 1996).

Translocated herbicides are an important tool in controlling weeds with extensive root systems. Failure to kill the root system will give rise to re-growth emerging from root fragments as indeed happened in this experiment with ragwort. Some plant species regenerate strongly from the root system when the shoot is either damaged or removed but not enough herbicide is applied to kill the root system (Hudson, 1955). There was no re-emergence of dead Scotch thistle shoots, probably due to its limited ability to reproduce by vegetative means.

Although the pot experiments showed that there is no need to increase herbicide concentration when applying only to the centre of plants, there is need to expand the research to field conditions. The plants in this experiment were probably relatively easy to kill because they were small compared to when they are traditionally sprayed in the field and were growing under ideal conditions with the roots restricted to a small volume of potting mix. In the field, applications tend to be late, requiring too much herbicide and thereby causing potentially more damage to pasture.

The effectiveness of herbicides is generally improved when plants are not under stress at the time of spraying, and are actively growing as was the case in this study (Rahman & James, 1991; Shaner, 1994). In addition, some of the herbicide solution applied to the centre of rosettes flowed down to the potting mixture and so was probably absorbed by roots. Triclopyr, picloram and metsulfuron are all readily absorbed by roots (Blair & Martin, 1988; Cox, 1998, Sarmah et al., 1998; Zimdahl, 1999) and the fact that roots were restricted in a pot could have increased this absorption. Thus, results in the field might be affected by soil type and rooting depth as well as the type of herbicide. Herbicides that are inactive in the soil such as glyphosate could possibly have had a different result.

It is interesting to note that the dose rate at which complete kill was achieved without any re-growth was only a fraction of the recommended rate Application of herbicides at rates below the recommended label dose has received considerable attention in recent years as a means of reducing overall herbicide use (Riethmuller-Haage, 2006). Herbicide labels give details on the recommended dosage rates and these rates are normally high enough to be effective under a wide range of conditions and under a range of operator skills to guarantee product performance (Cussans, 1992; Gonese & Weber, 1998; Mortensen et al., 2000). However, low herbicide rates are known to give variable results (Doyle & Stypa, 2004). Some of this variability was shown by the large standard errors on the dose response curves at the lowest rates (Figs 4.1 – 4.4).

The potential of the technique of spot spraying only the centre of weed plants was clearly shown using pot experiments and has opened up the potential for field research. If successful in the field, practical benefits such as reduced pasture damage are likely going to be realised.

4.5 Conclusions

The application of metsulfuron and triclopyr/picloram to only the centre 5% of the ragwort and Scotch thistle is equally effective in controlling weeds as full plant coverage but has the advantage of reducing the risk of pasture damage.

4.6 References

ANDERSON WP (1996) Weed Science: Principles and Applications. West Publishing Company. USA.

ASHTON FM & CRAFTS AS (1981) Mode of action of herbicides. John Wiley & Sons, New York.

BLAIR AM & MARTIN TD (1988) A review of the activity, fate and mode of action of sulfonylurea herbicides. *Pesticide Science* **22**, 195-219.

BOURDOT GW & KELLY D (1986) Density and cover estimates of some non-palatable herbaceous pasture weeds. In: *Proceedings 1986 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 183-186.

BOURDOT GW, SAVILLE D & SUNCKELL A (1994) Ragwort and Californian thistle - most important weeds in dairy pasture? In: *Proceedings 1994 New Zealand Plant Protection Conference,* Rotorua, New Zealand, 88-90.

BULLOCK JM, CLEAR HILL B, SILVERTOWN J & SUTTON M (1995) Gap colonization as a source of grassland community change: effects of gap size and grazing on the rate and mode of colonization by different species. *Oikos* **72**, 272-283.

COX C (1998) Picloram. *Journal of Pesticide Reform* **18**, 13-20.

CUSSANS GW (1992) Identifying ways of optimising herbicide use in crops. In: *Proceedings 1992 International Weed Control Congress,* 208-214.

DOYLE P & STYPA M (2004) Reduced herbicide rates - a Canadian perspective. *Weed Technology* **18**, 1157-1165.

GONESE JU & WEBER JB (1998) Herbicide rate recommendations: soil parameter equations vs. registered rate recommendations. *Weed Technology* **12**, 235-242.

HUDSON JP (1955) Propagation of plants by root cuttings. II. Seasonal fluctuation of capacity to regenerate from roots. *Journal of Horticultural Science* **30**, 242-51.

MCCONNAUGHAY KDM & BAZZAZ FA (1987) The relationship between gap size and performance of several colonizing annuals. *Ecology* **68**, 411-416.

MEEKLAH FA & MITCHELL RB (1984) Evaluation of herbicides for control of Californian thistle. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 20-23.

MORTENSEN DA, BASTIAANS L & SATTIN M (2000) The role of ecology in the development of weed management systems: an outlook. *Weed Research (Oxford)* **40**, 49-62.

NIELSEN OK, RITZ C & STREIBIG JC (2004) Non-linear mixed-model regression to analyse herbicide dose-response relationships. *Weed Technology* **18**, 30-37.

O'CONNOR B (2004) Novachem Manual 2004/2005. In: *Novachem Manual* (Novachem Services Limited), Palmerston North 488 pp.

POPAY AI, CORNWELL MJ & RAHMAN A (1985) Effects of metsulfuron-methyl on pasture. In: *Proceedings 1985 New Zealand Weed and Pest Control Conference,* Rotorua, New Zealand, 102-105.

RAHMAN A & JAMES TK (1991) Influence of soil moisture on the post-emergence activity of nine sulfonylurea herbicides. In: *Proceedings, 1991 Asian-Pacific Weed Science Society Conference.* **13**, 331-337.

RIETHMULLER-HAAGE I (2006) On the optimisation of low dosage application systems: improvement of dose advice and early detection of herbicidal effects. In: *On the optimisation of low dosage application systems: improvement of dose advice and early detection of herbicidal effects* (x + 134 pp). Wageningen Universiteit (Wageningen University), Wageningen Netherlands.

SARMAH AK, KOOKANA RS & ALSTON AM (1998) Fate and behaviour of triasulfuron, metsulfuron-methyl, and chlorsulfuron in the Australian soil environment: a review. *Australian Journal of Agricultural Research* **49**, 775-790.

SEEFELDT SS, STEPHENS JMC, VERKAAIK ML & RAHMAN A (2005) Quantifying the impact of a weed in a perennial ryegrass-white clover pasture. *Weed Science* **53**, 113-120.

SHANER DL (1994) Effect of environment on persistence and movement of herbicides in plants. In: Comparing glasshouse and field pesticide performance II. Proceedings of an international symposium held at the University of Kent, Canterbury, 12-14 April 1994. (129-138).

STREIBIG JC & GREEN JM (1994) How to compare glasshouse and field dose responses. In: Comparing glasshouse and field pesticide performance II. Proceedings of an international symposium held at the University of Kent, Canterbury, 12-14 April 1994. (173-180). British Crop Protection Council, Farnham UK.

STREIBIG JC, JENSEN JE, OLOFSDOTTER M et al. (1993) Dose-response curves in herbicide research. In: Integrated weed management for sustainable agriculture. Proceedings of an Indian Society of Weed Science International Symposium, Hisar, India, 18-20 November 1993. (Indian Society of Weed Science, Hisar, Haryana India.

THOMPSON A (1974) Herbicide effects on ragwort and pasture. In*: Proceedings 1974 New Zealand Weed and Pest Control Conference*, Nelson, New Zealand, 90-93.

ZIMDAHL RL (1999) Fundamentals of weed science. Academic Press, San Diego.

Chapter 5

5 Wiper application of herbicides to Californian thistle

5.1 Introduction

Californian thistle (*Cirsium arvense* (L.) Scop.) is one of the most troublesome weeds of pastures in New Zealand (Ivens, 1978; Bourdot et al., 1994) and is repeatedly included in lists of the world's worst weeds (Skinner et al., 2000). Its success depends on vegetative propagation via a creeping root system that survives winter and gives rise to new shoots in spring (Harrington & Ivens, 1983). The spread of the root system can be aggressive, growing horizontally by several metres in one season (Chancellor, 1970; Amor & Harris, 1974). Patches of Californian thistle may be formed from a single genotype, but often contain individuals from several genotypes.

Many highly effective herbicides are able to translocate and kill the root system but could at the same time be very damaging to pasture. Herbicides that are known to effectively control Californian thistle include clopyralid (Donald, 1988; Samunder & Malik, 1992), glyphosate (Grekul et al., 2005), metsulfuron, triclopyr (Bixler et al., 1991), and picloram (Heikes, 1964). These herbicides require selective application to the thistles to avoid damaging pasture. Weed wiping is an important technique for achieving thistle root kill with minimum damage to non-target species. Wiper application requires a height differential between the pasture and the target weed, which is normally achieved by grazing the pasture before treatment.

The well-developed root system makes Californian thistle difficult to control using most recommended methods, including herbicides (Haggar et al., 1986). It is important that herbicides translocate in sufficient amounts to kill the root system. Californian thistle, like any other plant, undergoes several growth stages during its life cycle. Root carbohydrate reserves are lowest when flowering begins and increase in early autumn as shoot growth declines (Wilson et al., 2006). The ability of the herbicide to be translocated to the root system depends on the growth stage of the plant.

Effective thistle control with herbicides requires taking advantage either of when roots are the strongest sink, or when carbohydrate reserves are at their lowest. During early flowering, the root does not act as a strong sink, especially for sugars from leaves on upper parts of the stem near flowers, and thus application of herbicide at this time using a wiper to upper leaves will result in limited herbicide transport to the roots (Harrington & Ivens, 1983).

Application of herbicides at the post-flowering stage is most likely to result in a higher proportion of herbicide moving into the root system (Wilson & Michiels, 2003). At this stage, the thistle will be replenishing its root reserves for the next growing season and translocated herbicides move together with sugars through the phloem to exert maximum injury to the roots. Research elsewhere has shown that clopyralid applied in autumn reduced thistle density by 92% at 8 months after treatment, whereas treatment made in the spring reduced plant density by only 33% (Wilson et al., 2006). Late spring application at the bud-to-early-bloom stage is also an important stage to control thistles after the plants have expended most of their energy to produce the spring flush. The removal of the shoot forces the plant to use its limited carbohydrate reserves for shoot re-growth.

There is great potential for increased use of weed wipers in pastures but farmers need to determine whether the benefits of control are greater than the damage caused to pasture. A study of the economics of impacts of the damage and other operational variables such as number of passes and speed is necessary for such an evaluation. Research in New Zealand has shown that wiper application takes only a fraction of the time needed to spot-spray an equivalent area (Makepeace & Thompson, 1982). These and other factors need to be considered for any economic study. Weed wipers, compared to broadcast-application of herbicides, have the potential to reduce the amount of herbicide used (Cramer & Burnside, 1980; Williams, 1989) and potentially reducing environmental contamination and spray-drift problems currently being experienced.

There are limited published data on the effectiveness of rotary weed wipers for controlling Californian thistle at different stages of growth in pastures using different herbicides and how these herbicides affect pasture. Where these data exist, the results from many authors are so variable that it is difficult to make any useful conclusions on the use of weed wipers in pastures (Thompson, 1983; Meeklah & Mitchell, 1984). To date there is also very limited information on the effects of wiping herbicides to tall growing plants on pasture, although Grekul et al. (2005) attempted to highlight possible causes of pasture damage.

The primary objective of the research in this chapter was to develop strategies for the control of Californian thistle using weed wipers in pastures. The specific objectives were: (a) to determine the effectiveness of translocated herbicides in controlling Californian thistle in a ryegrass/clover pasture, (b) to investigate the optimum growth stage for application of herbicides, (c) to investigate the effectiveness of double passes compared with a single pass of weed wipers, and (d) to evaluate any pasture damage caused by weed wiping.

5.2 Materials and methods

5.2.1 Study sites

Two field experiments were conducted on two sites and in two different seasons in an established perennial ryegrass and white clover pasture at the Keebles Sheep and Beef Cattle Research Farm of Massey University, Palmerston North, from January 2005 to October 2006. The soil type at both sites was a Tokomaru silt loam, a Planosol formed on loess and consisting of a fairly permeable silt loam (Magesan et al., 1999).

The area has an average annual rainfall of 960 mm and the average mean daily maximum temperature ranges from 22°C in February to 12°C in July (NIWA, 2007). Fig 5.1 shows the mean monthly rainfall and average maximum temperature for the trial period.

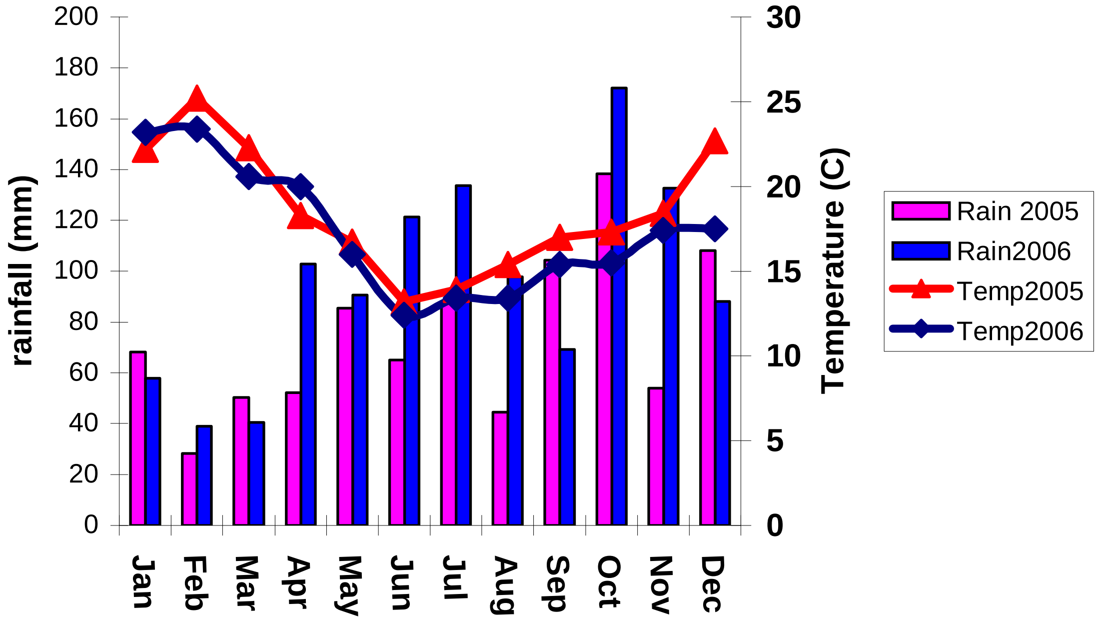


Fig 5.1 Total monthly rainfall (mm) and average maximum temperatures (°C) for the duration of the trial as measured at the local AgResearch weather station 1km from the trial site

5.2.2 Experiment 1

Experiment 1 compared the effectiveness at recommended rates of clopyralid (Versatill), glyphosate (Roundup GII), metsulfuron (Answer) and triclopyr/picloram (Tordon Gold), for the control of Californian thistle using a Rotowiper (Plate 5.1) at the early post-flowering stage. The Rotowiper consists of an absorbent carpet on a rotating drum (Rotoworks, 2007) . The carpet is kept wet by means of a 12-volt electrical pump.

Plate 5.1 The rotary weed wiper (Rotowiper) used in the field trials

The herbicide dilutions used are shown in Table 1. An organosilicone surfactant (Pulse Penetrant) at a rate of 1ml/L of herbicide solution and a detergent (Sunlight Liquid) at a rate of 1L/45 L water were added to each herbicide mix. The surfactant improves herbicide absorption by weeds and the detergent creates foam on the roller as a visual indicator of the roller wetness.

Table 5.1 The herbicides and rates used for the experiment

Trade name	Active ingredient	Rate (herbicide:water)
Versatill	Clopyralid 300 g/L	1:40
Roundup 360	Glyphosate 360 g/L	1:20
Answer	Metsulfuron 200 g/Kg	3g/litre
Tordon Gold	Triclopyr/picloram 100g&50g/L	1:20

Treatments were applied on 9 February 2005 when at least 80% of the plants were at the early-to-late post-flowering stage and the plants were covered in pappi. The second pass for double pass treatments was made at an angle of 180^0 to the first pass.

During treatment, pasture height was 5-8 cm and the roller height was set at 18 cm. The wiper was towed at 5 km/hr using a light vehicle (Plate 5.1) with narrow wheels (110 mm width) to minimise flattening of thistles by wheels. A different roller was used for each herbicide.

The maximum temperature on the day of application was 28.5^0C and no rain fell for 2 days afterwards. The thistle stem density and botanical composition of the pasture were assessed prior to treatment and throughout a period of 10 months afterwards. At the time of treatment the average thistle height was 1.1 m. The thistle plants were healthy, vigorously growing and of fairly uniform height prior to herbicide applications.

The experiment had a randomised complete block design with four herbicide treatments at two passes (single and double) and an untreated control replicated four times. Blocking allowed for differences in stage of development and density of the thistles within the plots. Each double pass plot was 3 m x 3 m in size but measurements were only taken from four 1 m x 1 m quadrats within each plot. For the single pass the plot size was 3 m x 1 m with the measurements being taken from two 1 m x 1 m quadrats. A distance of 1 m separated the single pass and double passes plots to minimise any possible interference effects.

Pasture composition was assessed by point analysis as described by Mountier & Radcliffe (1965), at 50 points/quadrat. Botanical composition was categorised into grass, clover, weed and bare ground. Since the pasture was predominantly perennial ryegrass and white clover, there was no attempt to differentiate these from other species of grass or clover.

Visual damage to thistles, grass and clover was assessed using a scoring system of 1-10. A score of 1 represented abundant clover of up to 15% composition while a score of 10 represented absence of clover in the plots. For grass, a score of 1 represented no visual injury while a score of 10 represented visual herbicide effect to all the grass. The final assessment was in December 2005.

5.2.3 Experiment 2

In Experiment 2 the effectiveness of herbicides for control of Californian thistles was compared at three growth stages, and safety of each product for pasture was again assessed. Apart from the triclopyr/picloram mixture all herbicides used in Experiment 1 were assessed again, using the same rates of herbicide, detergent and penetrant. Triclopyr/picloram had shown to be the least effective of the four herbicides in the first experiment, and was therefore not included in the second trial.

Treatments were applied on 26 January, 13 March and 2 April 2006 for the three stages of flower bud, early post-flowering (early post-bloom) and late post-flowering (pappi falling on to the ground) stages, respectively. The three herbicides (clopyralid, glyphosate and metsulfuron) were all used for the first two stages of flower bud and early post-flowering while only glyphosate was used for the last stage of late post-flowering as some plots were discarded due to poor condition of thistles. Many thistles were largely necrotic due to a combination of moisture stress and aphid infestation. A few days before the first treatment in January, most of the flower heads of the thistles had been eaten by sheep (26%) possibly due to excessive grazing pressure applied to eat pasture between thistle plants.

Pasture was generally grazed to an average height of less than 10 cm prior to treatment while the roller was set to a height of 18 cm for the first treatment, 16 cm for the second treatment and 23 cm for the third treatment depending on the height of the pasture plants not grazed prior to treatment. The thistles were not as uniform in height as was the case with Experiment 1 with a height ranging from 15-90 cm, although only a minority of stems (9%) were below the wiping height.

All the thistles were treated with a single pass. The single pass was chosen because it had given adequate control in the previous experiment (except for triclopyr/picloram), and the thistle density was much lower at the second site so a double pass was considered less necessary. The maximum temperatures and the number of days from application to onset of rain are shown in Table 5.2.

Table 5.2 The maximum temperature on the day of application and number of days from day of treatment to the onset of rain.

Thistle stage	Maximum temperature	Number of days before rain
Flower bud	21.0	3
Early post-flowering	19.4	7
Late post-flowering	21.8	0 (rained same day)

The plot sizes were 3 m x 3 m with measurements being taken from four 1 m x 1 m quadrats per plot. The experiment was a randomised block design with two herbicides (clopyralid and metsulfuron) applied at two growth stages and another herbicide (glyphosate) applied at three growth stages as well as an untreated control. Each treatment was replicated four times. Blocking was based on the thistle density of the plots. The wiper was towed at an average speed of 5 km/hr using the same vehicle as in Experiment 1. A different roller was used for each herbicide.

The thistle stem density and botanical composition of the pasture were assessed prior to treatment and regularly after treatment until October 2006. Pasture composition was assessed by means of point analysis (100 points/quadrat) and injury scores to grass and clover were recorded. The same scoring system was used as in Experiment 1. The average thistle stem density was 14 stems/m^2 and the average clover content of plots was 6.8%.

5.2.4 Experiment 3

A field experiment was conducted to investigate the effectiveness of metsulfuron for control of Californian thistles in three different directions, and assess the damage caused by wiping herbicides in one or two passes. The experiment was done on an established perennial ryegrass and white clover (*Trifolium repens* L.) pasture (the same one used in Experiment 2) at the Keebles Sheep and Beef Cattle Research Farm, Massey University, Palmerston North, from January to August 2007. The herbicide used was 200 g ai/kg metsulfuron as a methyl ester (Answer) at a rate of 3 g product per litre of water plus 0.1% Pulse Penetrant. A detergent was also added to the mix at a rate of 1L/45L water to create foam, as recommended by the manufacturers of Rotowiper (Rotoworks, 2007).

Treatments were applied on 28 February 2007 using the Rotowiper when at least 80% of the Californian thistle plants were at the early post-flowering stage. The maximum temperature on the day of application was 20.3^{0}C and no rain fell for seven days afterwards. Pasture was generally grazed to a height of less than 10 cm prior to treatment and the roller was set to a height of 20 cm. The wiper was towed at 5 km/hr using a light vehicle with narrow wheels to minimise flattening of thistles as earlier described.

The experiment was established as a randomised complete block design with four treatments and five replicates. The treatments were single pass, a double pass at 180^0 (i.e. the second pass was in the opposite direction to the first), a double pass in the same direction, and an untreated control. Blocking allowed for differences in clover density within the plots. The plots were 2 m x 2 m in size and all contained Californian thistle plants.

The Californian thistle stem density and the botanical composition of the pasture were assessed prior to and after treatment until August 2007. Pasture composition was assessed using point analysis at 200 points/plot. Botanical composition was categorised into grass, clover, weed and bare ground. Since the pasture was predominantly perennial ryegrass and white clover, there was no attempt to differentiate these from other species of grass or clover.

Damage to thistles, grass and clover was also assessed visually using a scoring system of 1-10. A score of 10 represented absence of clover in the plots while a score of 1 represented abundant clover. Point analysis of plots with a score of 1 showed them to have an average of 25% clover. On the damage to grass, a score of 1 represented no visual injury while a score of 10 represented visual damage to all the grass. At the time of treatment, the average thistle stem density was 41 stems/m^2 and the average clover content for all the plots was 18%. The thistle plants were healthy and vigorously growing at the time of treatment, with an average height of 60 cm.

5.2.5 Statistical analysis

The effectiveness of herbicides for thistle control was mainly determined by shoot re-emergence in each plot in the following spring expressed as a percentage of the initial thistle density. The data from quadrats were pooled together to give a single figure for each plot.

A similar analysis was done for clover content by assessing pre and post treatment abundance of clover for each plot. Because there was a number of zero values in the data, 1.5 was added to every observation to allow the use of log transformation (i.e. Log (Y+1.5) where Y denotes the response variable). The log transformations were necessary to normalise the data and meet the assumptions of ANOVA. Analysis of grass damage was based on injury scores. ANOVA on transformed data for all variables was performed using Proc GLM, SAS Version 9.1 (SAS Institute, 2004) for all statistical analyses and significance was set at $P<0.05$ for all comparisons. Similar Anova models as used in Section 3.2.6 were used in these experiments. However, back-transformed means are presented in the results below.

5.3 Results

5.3.1 Experiment 1

The various double pass herbicide treatments when assessed 10 months later resulted in significant effects ($P<0.05$) on all Californian thistle shoot density with glyphosate resulting in an average 0.85 stems/m^2 and triclopyr/picloram resulting in 2.6 stems/m^2, compared with 12.7 stems/m^2 in untreated plots (Table 5.3). Clopyralid and metsulfuron double passes resulted in 1.3 and 2.3

stems /m^2, respectively. A double pass for glyphosate and triclopyr/picloram was superior to a single pass in reducing thistle shoot re-emergence ($P<0.05$).

Table 5.3 The Californian thistle stem density resulting from single and double passes of a Rotowiper applying four herbicides from February 2005 to October 2005

Herbicide	Number of passes	Number of stems/m^2
Untreated control		12.7a
Clopyralid	single	3.4c
Clopyralid	double	1.3cd
Glyphosate	single	3.4c
Glyphosate	double	0.85d
Metsulfuron	single	3.0cd
Metsulfuron	double	2.3cd
Triclopyr/picloram	single	7.1b
Triclopyr/picloram	double	2.6cd

There was no difference between the single pass for clopyralid, glyphosate and metsulfuron. However, a single pass for triclopyr/picloram was not as effective as the other herbicide treatments.

Herbicide wiping treatments had a significant effect on the biomass of other species ($P < 0.05$), particularly white clover and low-lying weeds despite being under the height of the wiper. Clopyralid, metsulfuron and triclopyr/picloram almost completely eliminated white clover from the plots while the clover content of glyphosate-treated plots was not different from the untreated control (Fig 5.2). The clover content of clopyralid, metsulfuron and triclopyr/picloram treatments remained significantly less than that of the untreated control or glyphosate 10 months after treatment (Fig 5.2). The number of passes had no effect on the average number of prostrate weeds, grass damage or clover content.

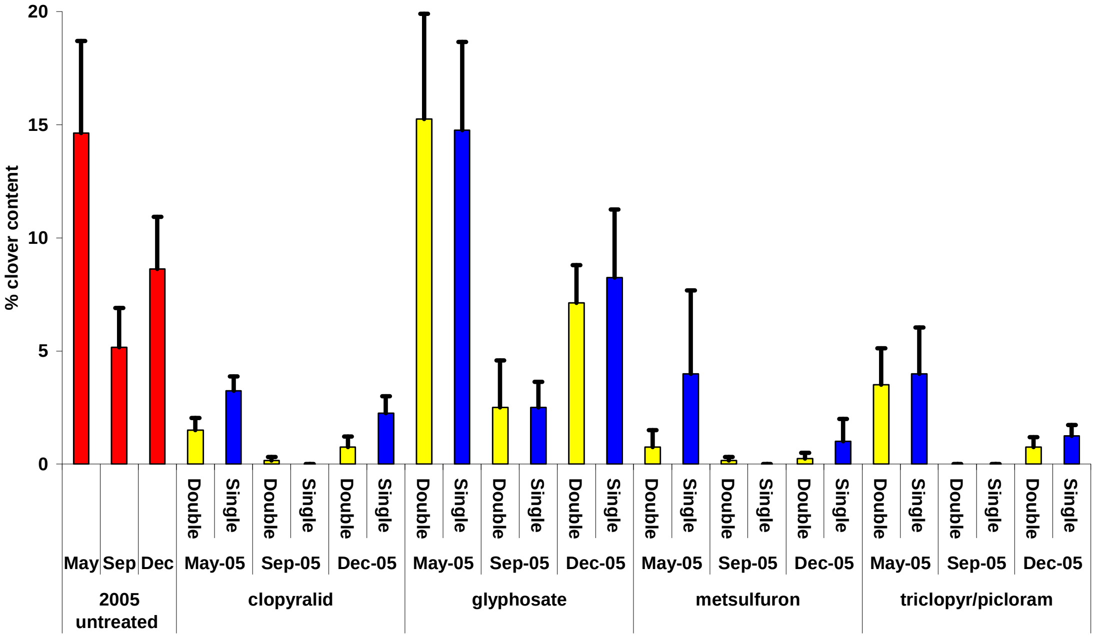


Fig 5.2 The clover composition of plots after herbicide application by a Rotowiper in February 2005. (Vertical bars refer to SEM, n=4).

Glyphosate and metsulfuron caused some short term grass damage as shown by localised patches of dead grass at the base of thistle stems though generally it was minimal (Table 5.4) with the damage symptoms having disappeared after 8 weeks. The dead grass did not create large bare patches and the grass quickly recovered. No grass damage was observed for clopyralid and triclopyr/picloram treatments.

Table 5.4 Injury scores to pasture grass for a double pass 5 weeks after application of herbicides, where 1 = total mortality and 10 = no effect. Scores with the same letter are not significant

Treatment	White clover score	Ryegrass score
Untreated control	10.0**a**	10.0**a**
Clopyralid	8.9**bc**	10.0**a**
Glyphosate	9.2**b**	9.3**b**
Metsulfuron	8.4**bc**	9.3**b**
Triclopyr/picloram	8.1**c**	9.9**a**

Herbicide wiping with metsulfuron also affected the occurrence of other prostrate weed species in the plots. Metsulfuron plots contained significantly fewer weeds (other than Californian thistles) (P<0.05) than for all other herbicide treatments three months after treatment (Fig 5.3). There was no difference in the occurrence of these weeds in untreated control compared to clopyralid, glyphosate, and triclopyr/picloram treatments.

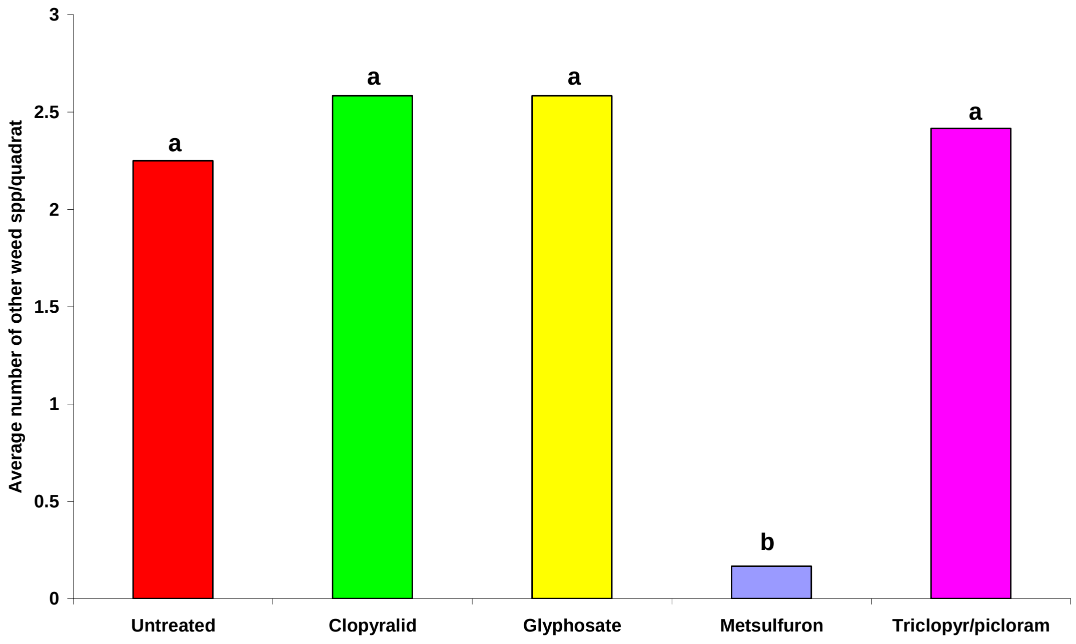


Fig 5.3 Average number of prostrate weeds per m^2 for a double pass 3 months after wiper application of herbicides by a rotary weed wiper. Means followed by the same letter are not significantly different (LSD, P< 0.05).

The following weeds were found in all other treatments but were absent in metsulfuron-treated plots: catsear (*Hypochoeris radicata* L.), dandelion (*Taraxacum officinale* L.), hawksbeard (*Crepis capillaris* (L.) Wallr.), hawkbit (*Leontodon taraxacoides* (Vill.)) Merat), creeping buttercup (*Ranunculus repens* L.), broad-leaved-plantain (*Plantago major* L.), narrow leaved plantain (*Plantago lanceolata* L.), pennyroyal (*Mentha pulegium* L.) and turf speedwell (*Veronica serpyllifolia* L.). A single plant of cleavers (*Galium aparine* L.) was found in one metsulfuron-treated plot.

5.3.2 Experiment 2

No treatment produced a significant decrease in Californian thistle stems compared with the untreated control in Experiment 2 when measured in October 2006 (Fig 5.4).

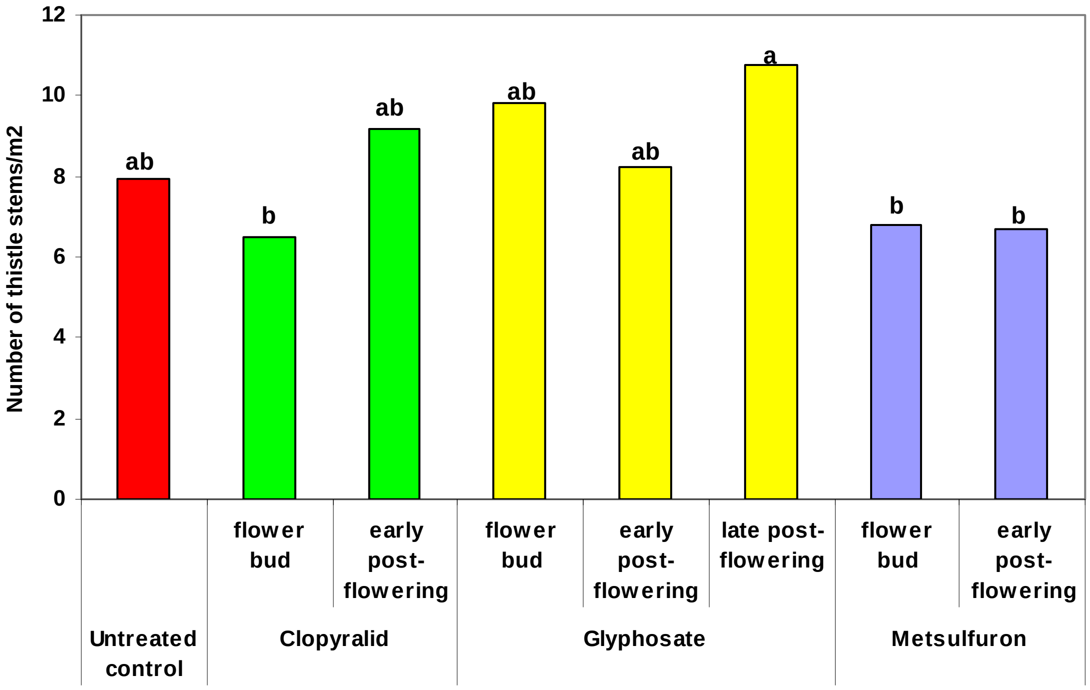


Fig 5.4 The number of Californian thistles stems/m^2 after Rotowiper application of herbicides at different stages. Bars with the same letter are not significantly different (LSD, P< 0.05).

The point analysis showed that the clover content of both metsulfuron treatments and glyphosate late post-flowering was significantly less than that of the untreated control (Fig 5.5).

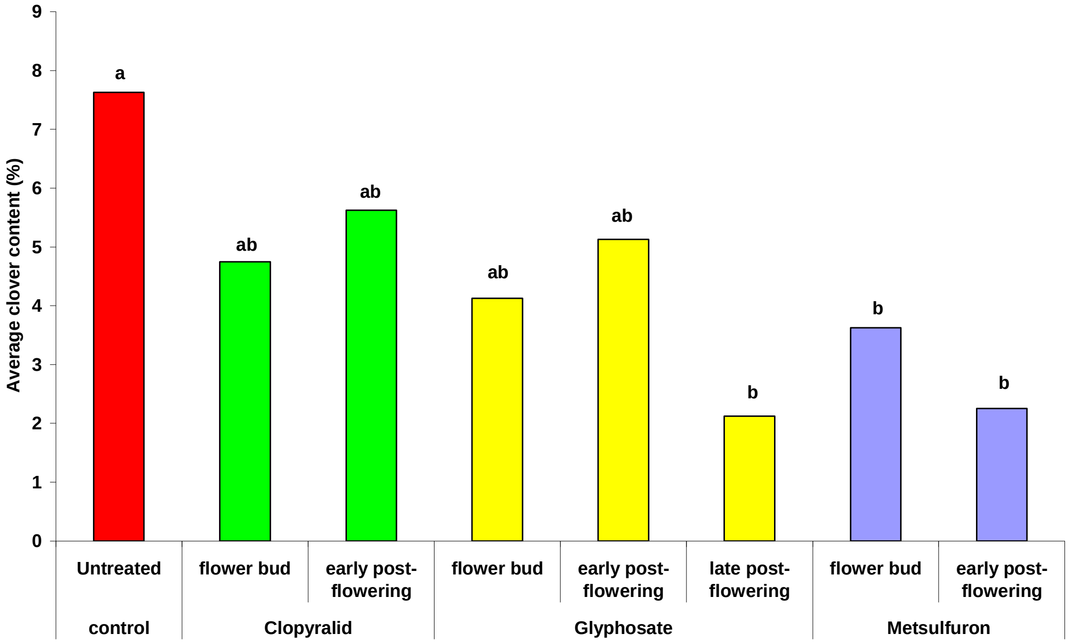


Fig 5.5 Average clover content of plots as measured by point analysis 6 weeks after application of herbicides by a Rotowiper. Bars with the same letter are not significantly different (P< 0.05).

Visual clover scores also showed similar results to that for point analysis, although it was probably a less sensitive measure of clover content as there was no difference between the untreated control and metsulfuron flower-bud stage (Fig 5.6).

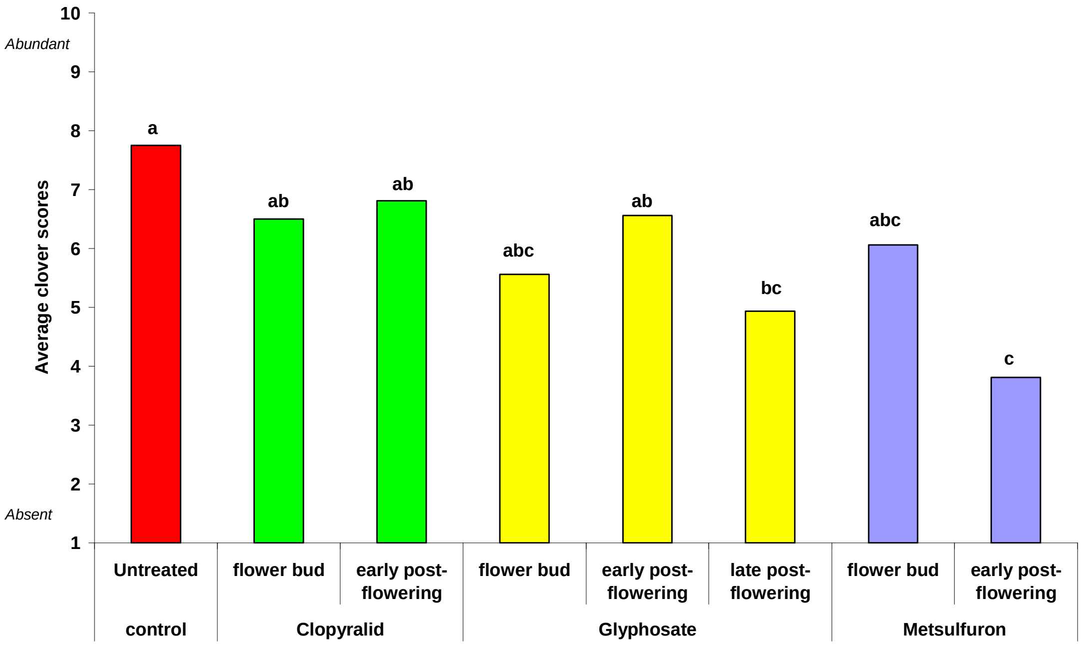


Fig 5.6 Average clover content of plots by visual scores 6 weeks after application of herbicides by a Rotowiper, where 1 = no clover present and 10 = abundant clover. Means followed by the same letter are not significantly different (LSD, P< 0.05).

There was no visible grass damage in any of the treated plots. The composition of the low-lying species was also not affected by treatments.

5.3.3 Experiment 3

The effectiveness of the herbicide in reducing the thistle stem density was generally low although a single pass and a double pass in one direction were more effective than the untreated control (Fig 5.7).

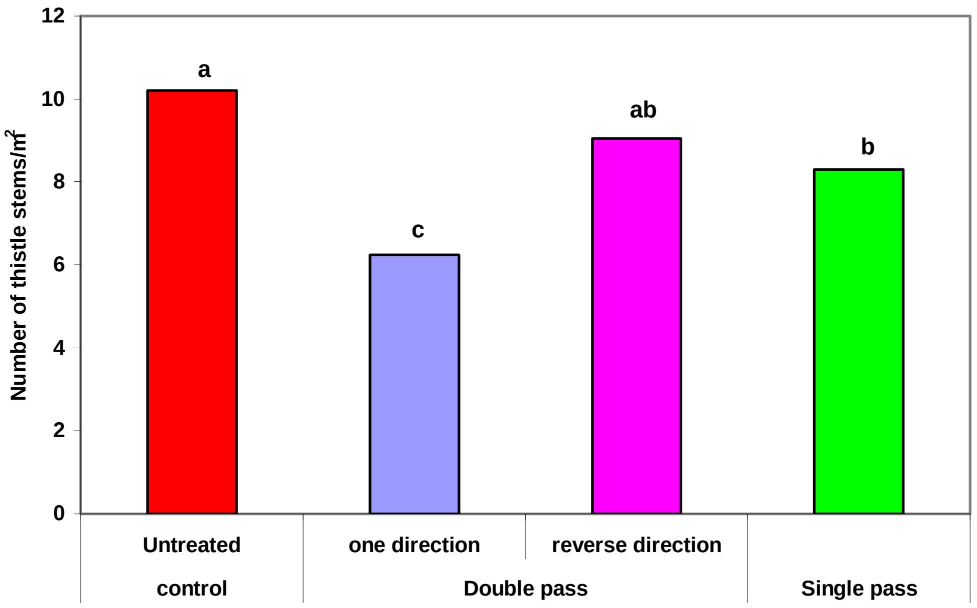


Fig 5.7 Average number of thistle stems/m^2 after metsulfuron treatment with a Rotowiper in different directions. Means followed by the same letter are not significantly different (LSD, $P< 0.05$).

Visual scores showed that there was no damage from any of the treatments suggesting that double passes are not more damaging than a single pass (Fig 5.8).

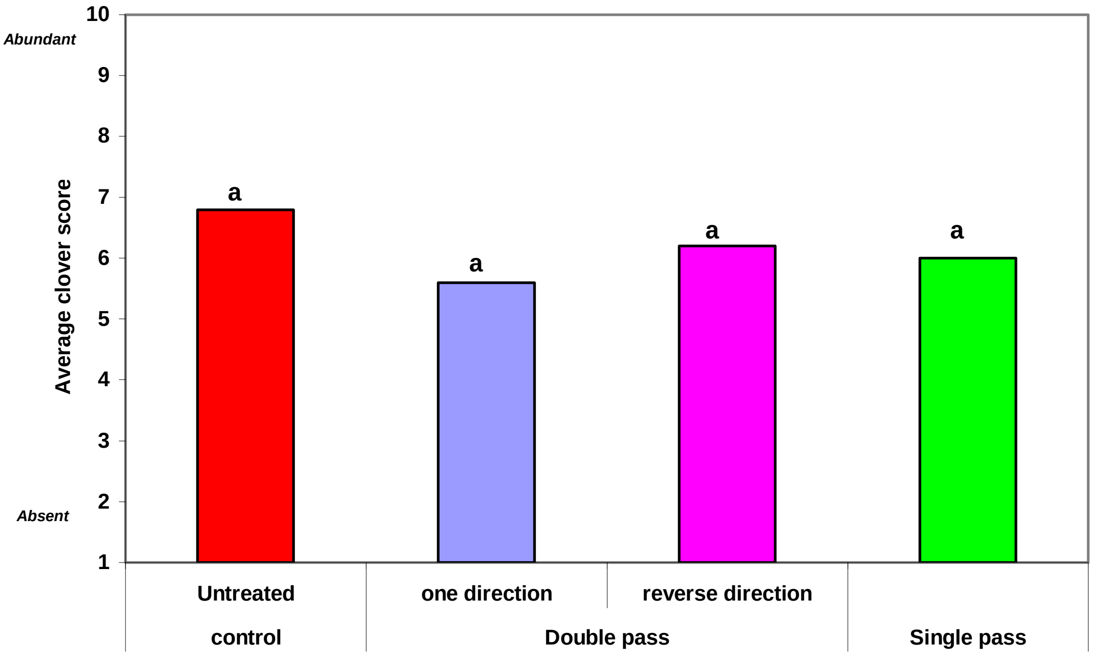


Fig 5.8 The effect on clover content of plots 6 months after single and double passes of a wiper applying metsulfuron to Californian thistle. Means followed by the same letter are not significantly different (LSD, $P < 0.05$).

5.4 Discussion

Compared with other published reports (e.g. Meeklah & Mitchell, 1984; Martin et al., 1990), the Californian thistle control levels in Experiment 1 are some of the highest ever observed for a one-off treatment of Californian thistle in pastures using weed wipers. If they can be consistently achieved, then this could become the treatment method of choice for selective control in pastures where the contours of the land allow use of a weed wiper. Complete control of Californian thistle generally requires more than a single herbicide treatment or a combination of control techniques (Haggar et al., 1986). Similar studies have shown that the effects of a single wiper application to thistles with glyphosate can last up to two years (Grekul et al., 2005). It would not cost much to do a follow-up treatment to wipe the remaining stems in the following year since the amount of herbicide applied is directly proportional to the thistle density.

However, comparison of different studies is difficult because some studies (Boerboom & Wyse, 1988a; Grekul et al., 2005) used 33% glyphosate which was much more concentrated than used in this experiment. It has been shown that more concentrated glyphosate is likely to result in poor thistle control as rapid tissue death leads to reduced translocation of the herbicide (Boerboom & Wyse, 1988b). However, Grekul et al. (2005) using 33% glyphosate achieved up to 80% control of Californian thistles. There is therefore potential to use more concentrated herbicide where necessary especially when the weed density is high.

Wiper application in two directions (Experiment 1) appeared to have increased the efficacy of glyphosate and triclopyr/picloram, probably by increasing the surface area of foliage to which the herbicide was applied. The superiority of double pass treatments could also be attributed to translocation of herbicides through the plant in sufficient quantities to kill the root. Most farmers would prefer to wipe only once and probably use much more concentrated herbicides to achieve the desired control.

The performance of the single (although effective) pass relative to the double pass treatment (Experiment 1) could have been compromised by the high density of thistles. When using weed wipers to treat plants, dosage applied per plant has been shown to decrease with increasing plant density (Mayeux, 1985). Although single pass treatments were not as effective as double pass treatments, they achieved a good level of control compared to some previous wiping trials. Wiping experiments using herbicides such as MCPB and combinations of MCPA and clopyralid on Californian thistles have resulted in less than 5% control and in some cases the number of shoots actually increased, while mixtures involving 2,4-D achieved control ranging from 25-38% (Meeklah & Mitchell, 1984). The probable reason why control was poor for the trials cited above is that phenoxy herbicides give inferior translocation compared to herbicides used in this study (Tomlin, 2000).

Variable results have also been achieved when thistles were treated at different stages. Thompson (1983) achieved 20% control at the bolting to bud stage and 66% control at full flower stage using glyphosate, whereas 2,4-D/picloram and 2,4-D/dicamba at bolting stage actually increased the number of shoots. Other wiper application studies using glyphosate to control Californian thistles in pastures achieved a reduction in thistle density of 68 to 80% during a three year period (Grekul et al., 2005). The same study also found that wiping at the flower bud stage was more effective than at later stages. However, the above comparison between different stages was done at different seasons and different sites making it difficult to make a valid conclusion. In contrast, pot studies have shown that application of glyphosate at the post-flowering stage is more effective than treating at earlier growth stages (Harrington & Ivens, 1983).

Glyphosate, although not statistically different from other double pass treatments in this study, would be the herbicide of choice when using weed wipers. Glyphosate caused less clover damage and it is a cheaper herbicide, making it an excellent herbicide for use with weed wipers. Triclopyr/picloram, besides being an expensive herbicide, was also the least effective on Californian thistle. More discussion on relative cost of herbicides and what influences the decision to choose one herbicide over another is presented in Chapter 8 (Section 8.2.2).

The most striking result from Experiment 2 was that the treatments were mainly ineffective. However, in contrast to Experiment 1, there was also less pasture damage. From the results, it is not possible to conclude the optimum growth stage for the control of Californian thistle using weed wipers. There are several reasons to explain the poor control of thistles in the second and third experiments. Firstly, applying herbicides at the flower bud stage means there is likely to be little movement of herbicides to the roots as the flowers act as a strong sink (Harrington & Ivens, 1983). Secondly, the thistles in Experiment 2 were severely stressed and this could explain the lack of effectiveness of the herbicides. Moisture stress is known to reduce the absorption and translocation of herbicides in plants (Lauridson et al., 1980; Rahman & James, 1991). Fig 5.1 shows the differences in the amount of rainfall in 2005 and 2006 for Experiment1 and Experiment 2, respectively. In addition, the plants were under severe stress from aphids with most thistles covered in sooty mould. Other than drought and insect pest damage, the other possible reason for the poor control could have been that the physiology of the plants was altered by removal of flower heads due to grazing pressure. Also, the weeds were generally small and a significant proportion would have been below the wiping height and did not receive adequate amounts of herbicides leading to poor control.

There was also poor control of Californian thistles in Experiment 3. Metsulfuron, the herbicide used in the experiment, is known for its variable control of Californian thistles according to a long time herbicide user and distributor of Weedswipers (Peter Thomson, 26 November 2007, *personal communication*). There was no obvious reason why a single pass and a double pass in one direction were the only treatments that were significantly different from untreated control. It is generally accepted that a double pass in opposite direction would improve herbicide coverage of the weeds.

Although wipers provide more selective application of herbicides than broadcast application, this study and research elsewhere have shown that some damage to pasture does occur from wiper application of herbicides (Makepeace & Thompson, 1982; Thompson, 1983; Martin et al., 1990). The damage to pasture recorded by these various authors was mostly localised and did not result in complete elimination of the clover as happened in some treatments in Experiment 1. There was little or no pasture damage in Experiments 2 and 3 as occurred in Experiment 1.

Various hypothesises have been proposed as to how the damage to pasture occurs. It is possible that this could be as a result of pressure of thistles against a roller causing dripping from the roller (Waddington & Bittman, 1987), or splattering from plants bouncing up after passing under the roller (Cessna et al., 1989), rainfall washing off herbicides from treated plants, and exudation (O'Sullivan & Kossatz, 1984; Hickman et al., 1989), among several other possibilities. It has also been shown that application of picloram to leafy spurge (*Euphorbia esula* L.) in pastures results in levels of residues in the soil similar to broadcast application at a given rate due to release by decomposition of plant tissue (Messersmith & Lym, 1985).

Rainfall after herbicide application appears to be the most likely cause of pasture damage. The total rainfall, its distribution, and the number of days between treatment of plants and onset of rain are likely to be important factors in determining the severity of the damage. The total rainfall and its onset after treatment was different for the three seasons, and this could have affected the response of thistles to herbicides as well as the differences in pasture damage (Table 5.5).

Table 5.5 The amount of rainfall and the number of days after treatment that it fell. The dates shown represent the time of the field trial with Feb 05 representing Experiment 1, Jan 06 – Apr 06 representing three field trials of Experiment 2, and Feb 07 represents Experiment 3.

Days after application	Exp 1 Feb 05 (mm)	Exp 2 Jan 06 (mm)	Exp 2 Mar 06 (mm)	Exp 2 Apr 06 (mm)	Exp 3 Feb 07 (mm)
1	0	0	0	0.4	0
2	0	0	0	1.6	0
3	8.4	0	0	2.8	0
4	3.2	0	0	1.2	0
5	0	0	0	0.2	0
6	6.2	0	0	5	0
7	5.4	0	0	4	0
8	0	0	0.2	9.8	0
9	0	5.2	12.2	13.8	0.24
10	0	0	0.8	0.6	0

In Experiment 1, rain fell only 3 days after application and a lot of herbicide could have been washed off on to pasture causing substantial damage. In Experiment 2, there was no rain for more than a week after treatment for the first two trials; hence, there was no pasture damage. In the third trial of Experiment 2, there was rainfall from the day of herbicide application and for the next nine days and this caused minimal damage to clover. Glyphosate washed off plants did not cause substantial damage as was also the case with the first field experiment showing that clover can tolerate low levels of the herbicide. There was also no damage in Experiment 3 since there was no rain for more than a week after treatment.

The possible causes of pasture damage are further explored in Chapter 6.

5.5 Conclusions

The best control of Californian thistle was achieved at the post-flowering stage with a double pass when plants were actively growing. Glyphosate, being the cheapest herbicide and the one that causes the least damage to pasture is the herbicide of choice for wiper application. Experiment 2 which tested different application dates was unsuccessful in terms of thistle control.

5.6 References

AMOR RL & HARRIS RV (1974) Distribution and seed production of *Cirsium arvense* (L.) Scop). in Victoria, Australia. *Weed Research* **14**, 317-323.

BIXLER LL, COOLEY AW & CARRITHERS VF (1991) Canada thistle control at two stages of plant growth with clopyralid. In: *1991 Proceedings of the Western Society of Weed Science, Seattle, Washington, USA,* 44-47.

BOERBOOM CM & WYSE DL (1988a) Influence of glyphosate concentration on glyphosate absorption and translocation in Canada thistle (*Cirsium arvense*). *Weed Science* **36**, 291-295.

BOERBOOM CM & WYSE DL (1988b) Selective application of herbicides for Canada thistle (*Cirsium arvense*) control in birdsfoot trefoil (*Lotus corniculatus*). *Weed Technology* **2**, 183-186.

BOURDOT GW, SAVILLE D & SUNCKELL A (1994) Ragwort and Californian thistle - most important weeds in dairy pasture? In: *Proceedings 1994 New Zealand Plant Protection Conference*, Rotorua New Zealand, 88-90.

CESSNA AJ, WADDINGTON J & BITTMAN S (1989) Residues of 2,4-D and picloram in aspen poplar and soil after application with a roller. *Canadian Journal of Plant Science* **69**, 205-212.

CHANCELLOR RJ (1970) Biological background to the control of three perennial broad-leaved weeds. In: *Proceedings 1970 British. Weed Control Conference,* 1114-1120.

CRAMER GL & BURNSIDE OC (1980) Control of common milkweed. In: *Proceedings 1980 North Central Weed Control Conference,*12-13.

DONALD WW (1988) Clopyralid effects on shoot emergence, root biomass, and secondary shoot re-growth potential of Canada thistle (*Cirsium arvense*). *Weed Science* **36**, 804-809.

GREKUL CW, COLE DE & BORK EW (2005) Canada thistle (*Cirsium arvense*) and pasture forage responses to wiping with various herbicides. *Weed Technology* **19**, 298-306.

HAGGAR RJ, OSWALD AK & RICHARDSON WG (1986) A review of the impact and control of creeping thistle (*Cirsium arvense* L.) in grassland. *Crop Protection* **5**, 73-76.

HARRINGTON KC & IVENS GW (1983) The influence of growth stage and application site on Californian thistle control by glyphosate. In: *Proceedings 1983 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 99-103.

HEIKES EE (1964) Tordon and other herbicides. Field testing for the control of deep-rooted perennial weeds in Colorado. *Down to Earth.* **20**, 9-12.

HICKMAN MV, MESSERSMITH CG & LYM RG (1989) Picloram release from leafy spurge (*Euphorbia esula*) roots in the field. *Weed Science* **37**, 167-174.

IVENS GW (1978) Californian thistle. *New Zealand Journal of Agriculture* **137**, 11.

LAURIDSON TC, WILSON RG & HADERLIE LC (1980) Effect of drought stress on Canada thistle control. In: *Proceedings 1980 North Central Weed Control Conference, 17.*

MAGESAN GN, SCOTTER DR & WHITE RE (1999) The utility of Burns's equation to describe solute movement through soil under various boundary and initial conditions. *European Journal of Soil Science* **50**, 649-656.

MAKEPEACE W & THOMPSON A (1982) Ragwort control using a rope wick applicator. In: *Proceedings 1982 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 256-260.

MARTIN P, FULLERTON DK & JAMES TK (1990) Weed trials using a rotary weed wiper. In*: Proceedings 1990 New Zealand Weed and Pest Control Conference*, Dunedin, New Zealand, 262-265.

MAYEUX HS, JR. (1985) Rates of herbicide applied on rangeland with a carpeted roller. In: *Proceedings 1985 Southern Weed Science Society Annual Meeting*, 263.

MEEKLAH FA & MITCHELL RB (1984) Evaluation of herbicides for control of Californian thistle. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 20-23.

MESSERSMITH CG & LYM RG (1985) Roller application of picloram for leafy spurge control in pastures. *Weed Science* **34**, 8-12.

MOUNTIER NJ & RADCLIFFE JE (1965) Problems in measuring pasture composition in the field. Observer variation with the point method. *New Zealand Journal of Botany* **3**, 243-252.

NIWA (2007) Summary of climate observations (National Institute of Water and Atmospheric Research. [Online]: Available: http://www.metservice.co.nz/default/index.php?alias=dataclimatesummaries192937 [Retrieved 21 August 2007].

O'SULLIVAN PA & KOSSATZ VC (1984) Absorption and translocation of 14C-3,6-dichloropicolinic acid in *Cirsium arvense* (L.) Scop. *Weed Research,* **24**, 17-22.

RAHMAN A & JAMES TK (1991) Influence of soil moisture on the post-emergence activity of nine sulfonylurea herbicides. In: *Proceedings, 191 Asian-Pacific Weed Science Society Conference*, 331-337.

ROTOWORKS (2007) Rotowiper. [Online]: Available: http://www.rotowiper.co.nz/Using.htm [Retrieved 21 August 2007].

SAMUNDER S & MALIK RK (1992) Evaluation of clopyralid against *Cirsium arvense*. *Tests of Agrochemicals and Cultivars*, **13**, 46-47.

SAS INSTITUTE (2004) Statistical Analysis System. SAS version 9.1.

SKINNER K, SMITH L & RICE P (2000) Using noxious weed lists to prioritise targets for developing weed management strategies. *Weed Science* **48**, 640-644.

TOMPSON A (1983) Pasture weed control by rope wick applicator. In*: Proceedings 1983 New Zealand Weed and Pest Control Conference*, Palmerston North New Zealand, 96-98.

TOMLIN CDS (2000) The Pesticide Manual. In: A World Compendium 1250. British Crop Protection Council, Surrey, UK.

TOOR RF (1994) Effect of applying glyphosate and clopyralid by rotary weed wiper on Californian thistle in Southland. In: *Proceedings 1994 New Zealand Plant Protection Conference*, Rotorua, New Zealand, 91-92.

WADDINGTON J & BITTMAN S (1987) Control of brush re-growth in north-eastern Saskatchewan by several concentrations of herbicides applied with a roller. *Canadian Journal of Plant Science* **67**, 467-475.

WILLIAMS GH (1989) The value of rope-wick applicators for weed control in mountain pastures. *Herba*, 6-8.

WILSON RG, MARTIN AR & KACHMAN SD (2006) Seasonal changes in carbohydrates in the root of Canada thistle (*Cirsium arvense*) and the disruption of these changes by herbicides. *Weed Technology* **20**, 242-248.

WILSON RG & MICHIELS A (2003) Fall herbicide treatments affect carbohydrate content in roots of Canada thistle (*Cirsium arvense*) and dandelion (*Taraxacum officinal*e). *Weed Science* **51**, 299-304.

Chapter 6

6 An investigation into the causes of pasture damage from wiper application of herbicides

6.1 Introduction

Wiper application of herbicides to weeds sometimes causes unintended damage to pasture (Makepeace & Thompson, 1982; Thompson 1983; Martin et al., 1990; Grekul et al., 2005). Vegetation growing under ungrazed tall weeds is often the unintended target from application of herbicides using weed wipers. This damage occurs when herbicides move from the treated target weeds or directly from the applicator. Despite claims by manufacturers for weed wipers that these applicators are selective and would only injure the target weeds, there is field evidence to support unintended herbicide effects on non-target vegetation as described in Chapter 5 and in other studies (Makepeace & Thompson, 1982; Thompson, 1983; Messersmith & Lym, 1985; Grekul et al., 2005).

Herbicide movement to non-target pasture can occur during and after application. During application, the most likely causes are direct physical contact, splatter, bouncing plants, and dripping from treated plants. Post-application damage due to loss of herbicides from foliage through rainfall is also a likely source of damage (Campbell & Nicol, 1998). It has also been postulated that when herbicides are applied directly onto plants, damage can be caused by translocation to roots then exudation into the soil, or release by decomposition of treated plants (Vanden Born, 1969; O'Sullivan & Kossatz, 1984; Hickman et al., 1990).

Insufficient height differential between pasture (especially grass seed-heads) and weeds can be a potential cause of pasture damage (Martin et al., 1990; Grekul et al., 2005). This can be due to direct injury or indirectly via translocation to interconnected plants. A young ryegrass tiller depends on the parent shoot for photo-assimilates until it has developed an independent shoot and root system (Fick & Moser, 1978; Matthew, 2002). Consequently, foliar-applied herbicides are likely to move together with photo-assimilates and this has the potential to injure daughter tillers (Forde, 1966; Nyahoza et al., 1974). Another possibility is the flowing of the herbicide down the outside surface of seed head stems and target weeds in contact with the wiper to the base of the plants causing localised damage.

It has also been suggested that the motion of the roller causes splatter that could hit non-target plants and cause damage to pasture. The treated weeds bouncing off the roller were also considered a possible cause. During field application of herbicides, foam bubbles could be seen falling off the wiper and there was a need to investigate whether this could be another potential source of pasture damage.

Root exudation, defined as the release of substances from inside the plants by either secretion or passive movement into the surrounding media by plant roots (Rovira, 1969) has also been proposed as a potential source of pasture damage. Root exudation is influenced by several factors including the age and species of the plant, temperature, water stress, light and the type of chemicals applied to the foliage (Hale et al., 1971).

Several herbicides including dicamba, glyphosate and picloram have been shown to move from the treated plant and cause injury to the untreated neighbouring plants through exudation (Linder et al., 1958; Linder et al., 1964; Hurtt & Foy, 1965; Coupland & Caseley, 1979; Coupland & Peabody, 1981; Gubbiga et al., 1996). Phloem-mobile herbicides have been shown to be exuded unchanged from the roots of treated plants (Coupland & Caseley, 1979) with exudates of glyphosate averaging 3% of the quantity applied to foliage of couch grass (*Elytrigia repens* L.) over eight days. Some studies have also demonstrated the presence of herbicides in guttation drops but at very low concentrations and so unlikely to cause any significant damage to untreated plants nearby (Coupland & Caseley, 1979).

Rainfall washing off foliar-applied herbicides was also proposed as a potential source of damage to pasture. However, if rainfall is responsible for pasture damage by washing wiped herbicides off weeds, then the amount of rainfall, its duration, and intensity as well as the period between application and onset of rain are presumably vital (Gerber et al., 1983; Bryson, 1987). The quantity of herbicide washed off would depend on dose, concentration, and herbicide formulation among other factors.

Addition of adjuvants generally improves penetration and retention thereby minimising the quantity of foliar applied herbicides being washed off by rainfall (Miller et al., 1998; Penner, 2000). The oil soluble ester formulations are generally less affected by rainfall than water soluble herbicides (Bovey & Diaz-Colon, 1969). Herbicides that are not absorbed after foliar application are susceptible to washing off by rain.

Herbicides washed off foliage during rainfall would land on pasture and soil where they are absorbed by plants causing damage to pasture. Soil-acting herbicides such as triclopyr, picloram, metsulfuron and clopyralid, can be absorbed through the roots (Tomlin, 2000) whereas herbicides like glyphosate would be rendered inactive (Sprankle et al., 1975).

Despite all the possible means by which herbicides could end up contacting pastures from wiper application, no study has been done to investigate the relative importance of these factors. This study aims to determine the relative importance of probable factors that cause damage to pasture from wiper application of herbicides to weeds.

6.2 Materials and methods

6.2.1 Experiment 1

The objective of this experiment was to investigate the effect of wiping herbicides on to seed heads on pasture damage. Perennial ryegrass (*Lolium perenne* L.) tillers were transplanted on 24 September 2006 from the Moginie Pasture and Crop Research Unit of Massey University, Palmerston North. The cores used were 10 cm diameter and 8 cm deep. Each soil core contained an average of 30 tillers. The soil cores were transplanted into 2000 cm^3 PB3 bags that had been filled with 400 cm^3 of vermiculite.

The plants were grown in a glasshouse and water was applied to the base of the plants using capillary matting wetted by means of drip hoses, occasionally supplemented by overhead watering. After the seed heads had emerged it became possible to weed out other grasses growing among the ryegrass. The seed heads were prevented from falling sideways on to neighbouring plants by using bamboo sticks and strings to keep them growing upright.

The herbicides were applied on 20 December 2006 when plants were at the grain-filling stage. The herbicides were wiped using a paper towel moistened with the appropriate herbicide from the uppermost (flag) leaf upwards, an average of 30 cm of stem. The average height of the seed heads was 60 cm. The herbicides used were 200 g ai/kg metsulfuron as a methyl ester (Answer) at a rate of 3 g product per litre of water, and glyphosate in the form of 360 g ai/L glyphosate as the isopropyl amine salt (Roundup Renew) at a rate of 1:19 herbicide to water.

The experiment was a randomised complete block design with three treatments (glyphosate, metsulfuron, untreated control). Each treatment was replicated ten times. Plants were allocated to blocks based on the number of seed-heads per pot.

Regular assessment of damage to vegetative daughter tillers growing underneath the seed head was done by means of injury scores. Visual assessments of foliar injury symptoms such as discoloration, twisting and necrosis were recorded on a scale of 1-10 with a score of 1 representing no visual herbicide injury and 10 representing complete necrosis. The scoring was done until 1 February 2007 when plants were carefully dissected to count all the live and dead tillers in each pot. Analyses of variance (ANOVA) of visual scores and tiller counts were carried out using the statistical software package SAS (SAS Institute, 2004).

6.2.2 Experiment 2

The objective of this experiment was to investigate the occurrence and significance of exudation of foliar-applied herbicides from Californian thistle plants growing in the same pot as white clover plants and relate this to pasture damage in the field. Californian thistle root fragments were collected on 8 November 2006 from the field at the Moginie Pasture and Crop Research Unit of Massey University, Palmerston North. The root fragments were planted into 2000 cm^3 PB3 planter bags with potting mix as described for Section 4.2.1. The roots measuring at least 5 cm in length were planted in a horizontal position.

The plants were grown in a glasshouse and water was applied to the plants using capillary matting as in Experiment 1. White clover seeds were then sown into the same planter bags on 11 Dec 2006 at a rate of 70 seeds (0.05 g) per bag.

The plants were treated with herbicides on 9 February 2007 using a Rotowiper. Two herbicides were used: a mixture of 100 g/litre picloram as an amine salt plus 300g/L triclopyr as a butoxy ethyl ester (Tordon Brushkiller) at a rate of 1 part herbicide to 39 parts of water, and 200 g ai/kg metsulfuron as a methyl ester (Answer) at a rate of 3 g product per litre of water. The maximum temperature on the treatment day was 25.3 ^{0}C.

The plants were arranged in a single row on asphalt pavement supported by concrete blocks. The pots as well as the clover growing in them were completely covered by a plastic skirt to prevent any contamination of the clover with herbicide from the wiper. At the time of treatment, both the thistles and clover plants had well developed root systems. The thistles were at the early post-flowering stage and averaged 60 cm in height. The height of the planter bag was 14 cm while the height of the wiper was set at 20 cm. After treatment and when the plants had dried in the sun and the plastic skirts removed, they were taken back to the glasshouse where they were randomly positioned on sub-irrigated benches. The mean daily temperature in the glasshouse ranged from a high of 23.2^{0}C in February to a low of 14^{0}C in May for the duration of the experiment.

The experiment was a randomised complete block design with three treatments, i.e. the two herbicide treatments and an untreated control. Plants were allocated to blocks based on the amount of clover in each pot. Each treatment was replicated ten times.

Visual assessments of foliar injury symptoms were conducted as in Experiment 1. The scoring occurred on average every 3 weeks until 14 May when both the thistles and clover were separately harvested. The fresh weight of both clover and thistle was recorded before they were dried in the oven at 80^{0}C for 24 hours and weighed again. ANOVA of visual scores, fresh and dry weights were carried out using the statistical software package SAS (SAS Institute, 2004).

6.2.3 Experiment 3a

This experiment investigated the effect of splattering and dripping of herbicide from the roller of the Rotowiper on pasture damage. The experiment was done from 10-13 January 2007 on asphalt pavement using an artificial weed structure and Petri dishes to collect the herbicide. The herbicide used was clopyralid in the form of a 300 g/L amine salt (Versatill) at a rate of 1:39 herbicide to water. Clopyralid was chosen after preliminary experiments showed it was the easiest herbicide to detect at low concentrations using a UV–VIS spectrophotometer (Hitachi, Model U2000). The measurement of unknown concentrations of herbicides using a spectrophotometer is discussed further in Chapter 7.

The artificial weed structure consisted of a 4.2 m long wooden beam on which five artificial weeds were evenly spaced 90 cm apart (Plate 6.1). Each “weed” was made from a length of flexible drainage pipe inside which a flexible PVC rod was placed, anchoring it upright to the beam. Each “weed” was 75 cm in height and 5 cm diameter. The “weeds” were covered in plastic bags that were removed and discarded after each run.

Four Petri dishes (90 mm diameter x 15 mm depth) together with their lids were placed around each “weed” with two dishes directly under the artificial “weed” while the other two were off-set 15 cm away on the other side of the supporting beam (Plate 6.1).

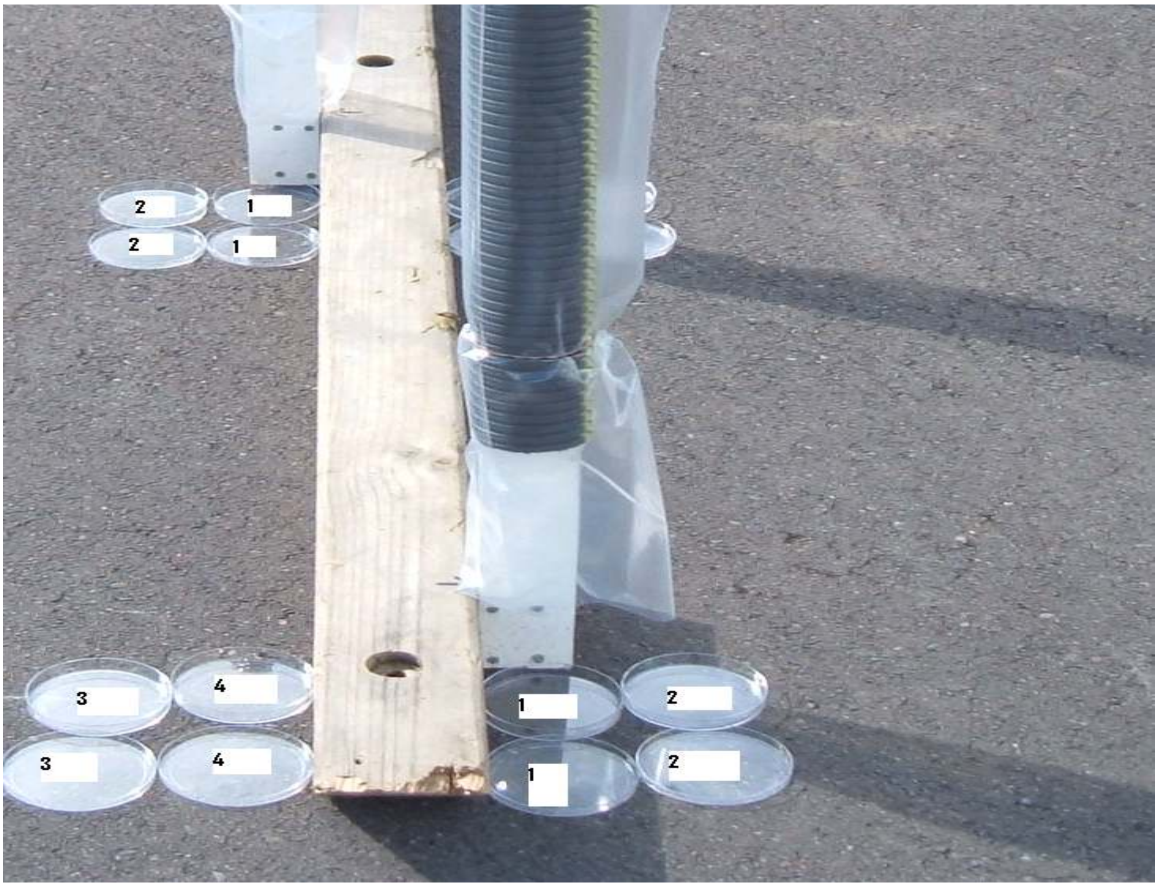


Plate 6.1 Arrangement of Petri dishes around the artificial weeds. The same number represents the dish and its lid.

Each run (replicate) had a total of 20 dishes. For each treatment, Petri dishes were placed exactly on the same positions. The placement of each Petri dish in relation to the weed structure was recorded.

The experiment was a factorial design with three wipers (Eliminator, Rotowiper and Weedswiper), two speed levels (5 & 10 km/hr) and two “weed” situations (presence or absence of the weed structure) replicated three times. There were two untreated controls. For the untreated controls, the Petri dishes were placed with and without the artificial weeds but without driving the wipers over.

The Eliminator and Rotowiper were towed using a quad bike whereas the Weedswiper was mounted on the rear of a tractor on a three-point-hitch that is hydraulically adjusted so it can be set at a desired height. The wipers were set at a height of 20 cm. The three wipers were driven over the dishes at two different speeds of 5 and 10 km/hr with the weed structure present and then without the weed structure to separate the effects of splatter due to the motion of the wipers and herbicide flowing down the artificial weeds.

After treatment, the dishes had their lids replaced and were taken to the laboratory where they were each washed with 10 ml of water and a sample of each resultant solution analysed by a spectrophotometer. The Petri dishes were washed with water from 15-19 2007 January after being stored in the cold room at 4^{o}C. Preliminary experiments had shown that storing the dishes in the cold room for up to a week did not have any effect on the quantity of herbicide collected. The technique to estimate the herbicides in Petri dishes using a spectrophotometer is further described in Chapter 7.

ANOVA on quantities of herbicide collected in each Petri dish was performed on log transformed data (log (y+1.5)) where y was the original data. The statistical software package SAS (SAS Institute, 2004) was used for the analysis.

6.2.4 Experiment 3b

This experiment investigated the effect of splattering and dripping of herbicide from the roller of the Rotowiper on pasture damage. The experiment was done in the field at No. 4 Dairy Farm of Massey University on clumps of rushes (*Juncus sarophorus* L.A.S.Johnson). The herbicide clopyralid at the same rate as in the previous experiment was applied on 1 March 2007.

Petri dishes were clustered around clumps of rushes. The experiment design was 10 clumps of rushes surrounded by 10 Petri dishes so there was a total of 100 dishes. Eight dishes were clustered 15 cm from the clump, two on each side (each set of two dishes placed at an angle of 90^0 to the next set), with another two dishes placed in front of the clump at a distance of 1m from the clump and so was passed over before the clump was wiped to serve as control (Fig 6.1).

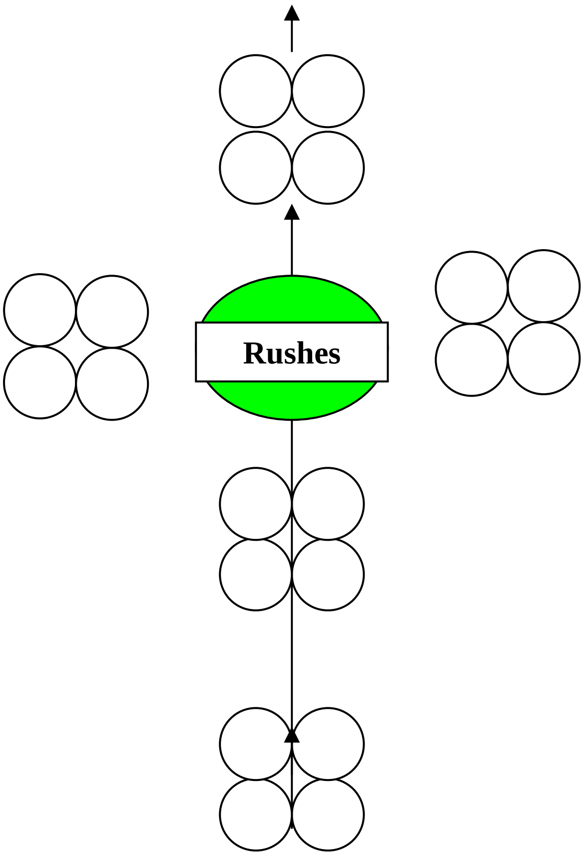


Fig 6.1 The arrangement of Petri dishes (and their lids) around clumps of rushes. The arrow indicates the direction of travel of the wiper.

The clumps were on average 45 cm in diameter and 60 cm in height with an average of 280 stems per clump.

The Rotowiper was then driven over the clumps at an average speed of 5km/hr. The wiper was set to a height of 20 cm. After treatment, the dishes were taken to the laboratory where they were washed with 10 ml of water and the resultant solution put through a spectrophotometer as described earlier.

6.2.5 Experiment 3c

This experiment investigated the resistance of weeds to the motion of the wiper and how this might affect the amount of herbicide dripping down the surface of the weed as well as splattering of herbicide from weeds springing up from underneath the wiper. The experiment was done on asphalt pavement at Massey University.

Three clumps of rushes of similar size as used in Experiment 6.2.3 (b) and an artificial weed structure (Plate 6.1) were used for the experiment. The rushes were collected from the same field as for the field experiment. Both the artificial weeds and rushes were placed in front of a sliding gate between the gate and a steel frame. A rope was attached to the top of the sliding gate with a bucket attached on the other end hanging on the steel frame. Water was added to the bucket forcing the sliding gate to move over the rushes and artificial weeds. The volume of water needed to push the gate over the weeds was then converted to Newtons as a measure of the force required for the gate to move over the weeds. The process was repeated three times for each of the three clumps of rushes and three times for each of the five artificial weeds.

6.2.6 Experiment 4

The objective of this experiment was to investigate rainfall washing off herbicides from treated plants on to pasture. Californian thistle root fragments were collected on 6 October 2006 from the same field as used for Experiment 2. The plants were grown using the same methods and conditions as in

Experiment 2 except that no white clover was sown in the planter bags for this experiment.

White clover and perennial ryegrass were grown in separate 200 cm^3 pots using the same potting mix as described in Section 4.2.1. Clover seed was sown on 5 January 2007 at a rate 35 seeds (0.025 g) per pot. Perennial ryegrass seed was sown on 10 January at a rate of 32 seeds (0.1 g) per pot. The plants were grown in the glasshouse and irrigated as described in Experiment 2 but with occasional supplementary overhead watering.

The herbicides used and herbicide rates were exactly as in Experiment 2. A different roller was used for each herbicide. The thistles were treated on the asphalt pavement as in Experiment 2 on 9 February 2007. After treatment and once the thistle plants had dried in the sun, they were transferred to the field laboratory. Using a rainfall simulator delivering 246 mm of water per hour, plants received rainfall 1 or 5 days after the herbicides were applied. The thistles were placed under the simulator for 30 seconds thus receiving equivalent to 2.0 mm of rainfall. Four pots each of clover and ryegrass were placed around each Californian thistle plant during rainfall simulation to intercept any herbicide that washed off the treated thistle. There were a total of 24 pots (for six thistle pots) each of clover and ryegrass pots for all the treatments.

The experiment was a randomised complete block design with four herbicide treatments, two untreated controls, and two simulated rainfall periods (1 day & 5 days) after treatment. Treatments were blocked on the size of the thistle plants. Each treatment was replicated six times.

Visual assessments of foliar injury symptoms were recorded by means of scores for the perennial ryegrass and white clover plants as described for Experiment 2. The scoring was done approximately every three weeks from the day of simulated rainfall for the two rainfall events respectively, until 18 April when both the ryegrass and clover were separately harvested. The harvesting was done on 13 and 17 April for the plants that were washed on

Day 1 and Day 5 respectively. The fresh weight of both clover and ryegrass was recorded before they were dried in the oven at 80^0C for 24 hours and weighed again. ANOVA of visual scores, fresh and dry weights were carried out using the statistical software package SAS (SAS Institute, 2004).

6.3 Results

6.3.1 Experiment 1

There were no significant differences in the number of necrotic tillers in all treatments (Fig 6.2). The average number of necrotic tillers per pot was 1.1%, 3.6% and 4.4% for untreated control, metsulfuron and glyphosate, respectively. There was a huge variability in the number of necrotic tillers from pot to pot making it hard to detect any treatment differences. All treated panicles were visibly necrotic from the herbicides 6 weeks after treatment when the plants were dissected to count the daughter tillers. The visual damage scores for all the treatments were similar as there was no visual damage to the daughter tillers until plants were dissected.

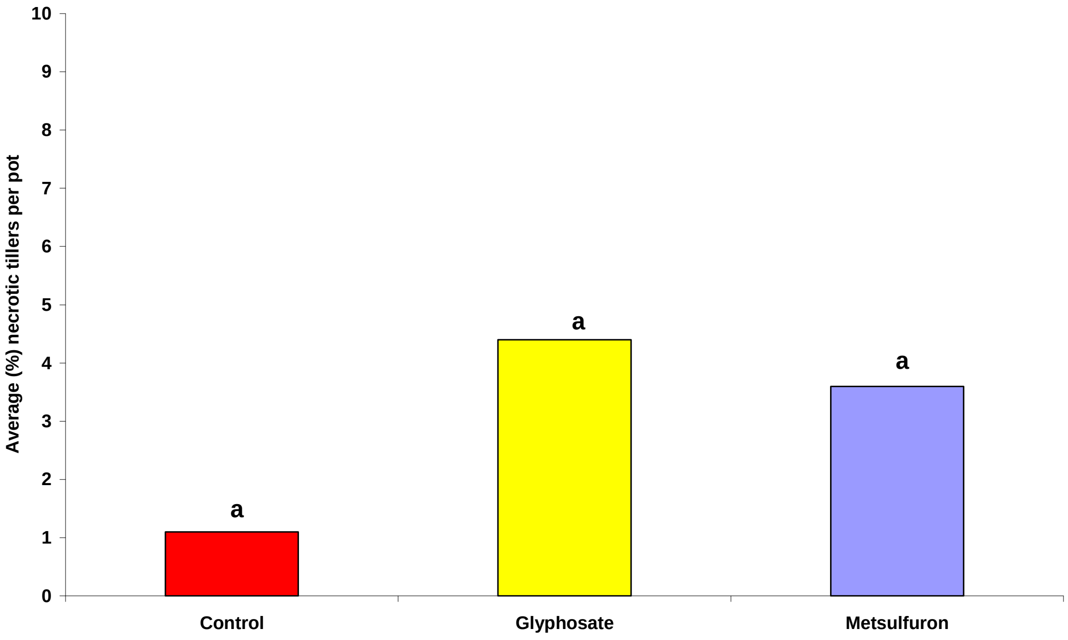


Fig 6.2 Herbicide effects on tiller necrosis six weeks after treatment with glyphosate and metsulfuron. Means followed by the same letter are not significantly different (LSD, $P< 0.05$).

6.3.2 Experiment 2

Clover plants growing under Californian thistle plants treated with metsulfuron had significantly less dry weight than both the untreated control and triclopyr/picloram (Fig 6.3). Visual injury scores also showed a similar result

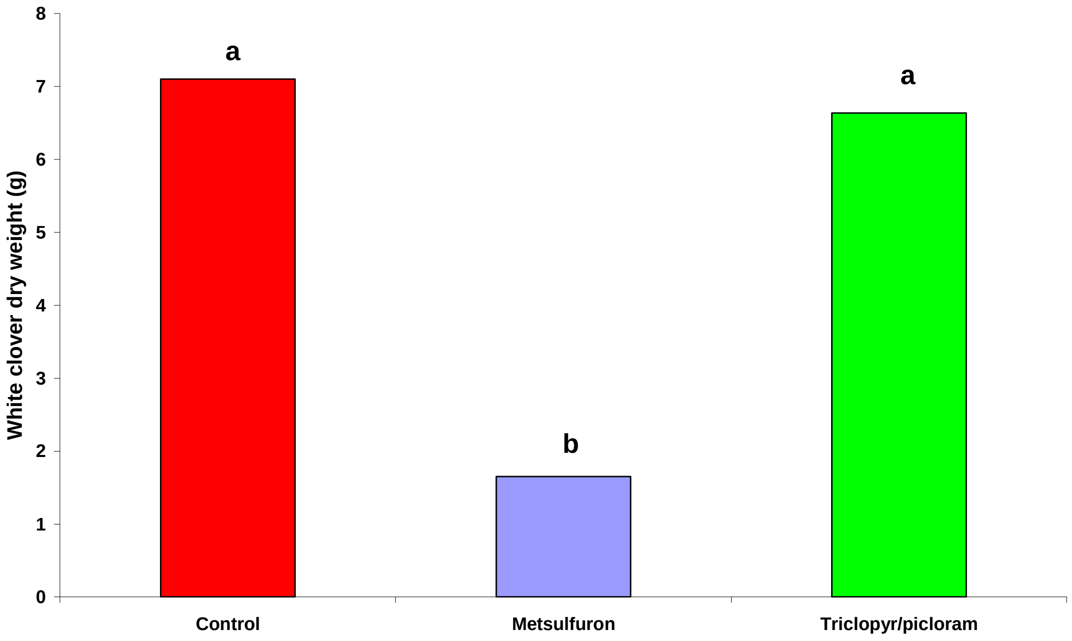


Fig 6.3 The dry weight (g/pot) of clover growing under treated Californian thistle plants 13 weeks after metsulfuron and triclopyr/ treatment. Means followed by the same letter are not significantly different (LSD, $P < 0.05$).

However, the dry weight of the thistle stems suggests that metsulfuron and triclopyr/picloram had similar damaging effects on the thistles and were both significantly different from the untreated control (Fig 6.4). Injury scores on thistle stems showed a similar result to the dry weight. Some of the thistles did not die as a result of the treatments with only 60% and 70% mortality for metsulfuron and triclopyr/picloram respectively probably due to insufficient herbicide being applied.

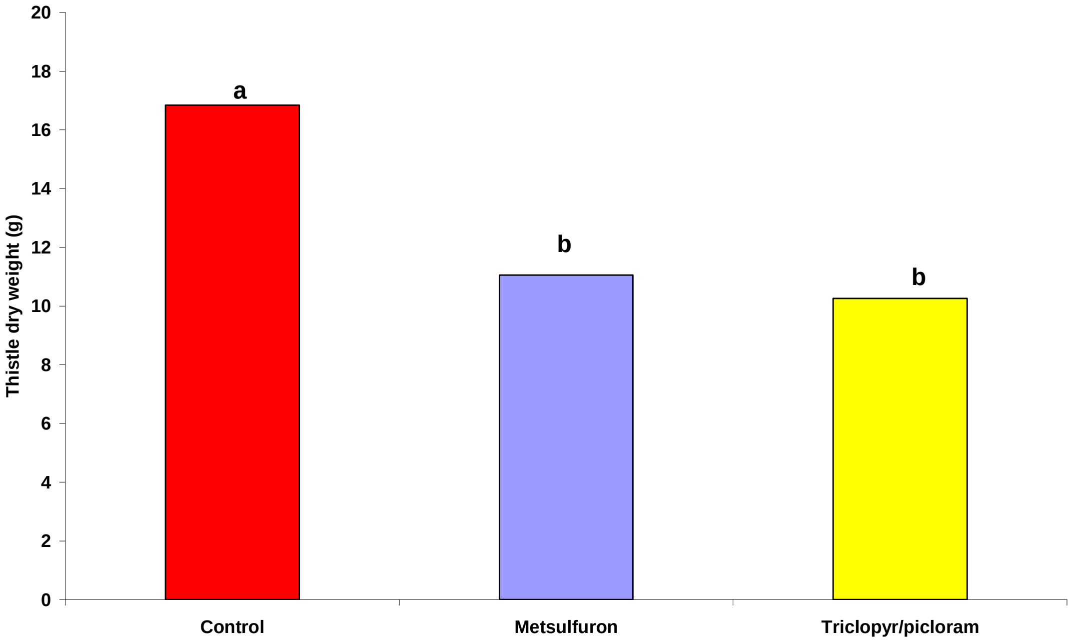


Fig 6.4 The dry weight (g) of Californian thistle plants 13 weeks after metsulfuron and triclopyr/picloram treatment. Means followed by the same letter are not significantly different (LSD, $P < 0.05$).

6.3.3 Experiment 3a

There were significant differences ($P = 0.05$) in the amount of herbicide collected in Petri dishes on the ground around the base of the artificial weeds with the Rotowiper having the highest amount while the Weedswiper had the least (Fig 6.5).

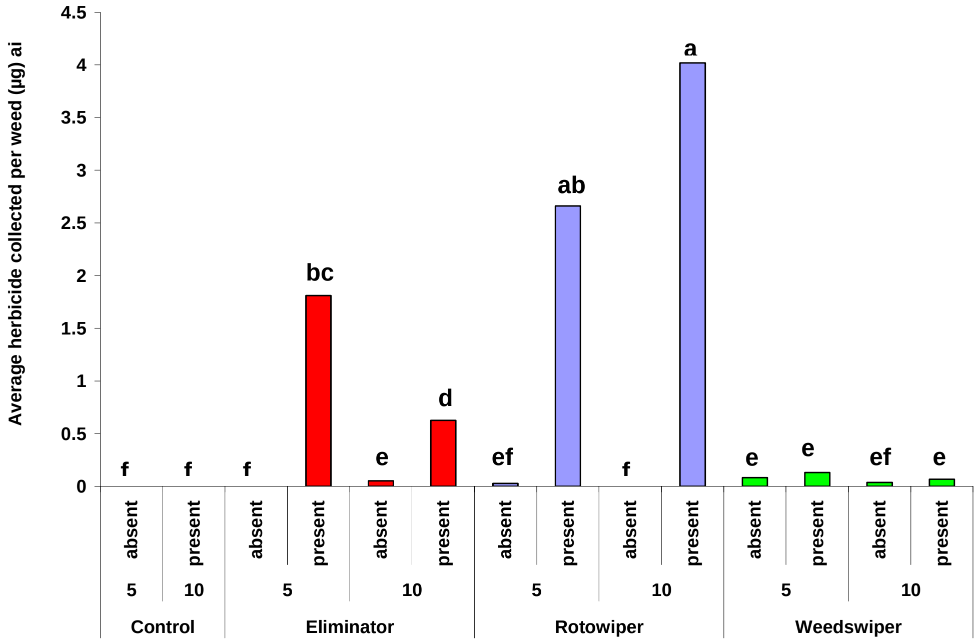


Fig 6.5 The relationship between type of applicator, speed and presence or absence of weeds on the amount of herbicide collected in Petri dishes. Means followed by the same letter are not significantly different (LSD, $P< 0.05$).

There was no consistent trend in the effect of speed on the herbicide collected in Petri dishes. The slower speed resulted in more herbicide being collected from the Eliminator (Fig 6.5) while speed had no effect for both the Rotowiper and the Weedswiper.

The presence or absence of the "weed" structure had a significant effect on the amount of herbicide collected with more herbicide collected in the Petri dishes when the artificial weeds were present than when absent (Fig 6.5).

The amount of herbicide collected in Petri dishes was dependent on the position of the dish for the three wipers. The positions of the dishes are shown in Plate 6.1. Position 1 picked up more herbicide than any other position for all three wipers. Position 2 for the Rotowiper picked up more herbicide than positions 3 & 4. There was no difference between Positions 2, 3 and 4 for the Eliminator and Weedswiper (Table 6.1).

Table 6.1 The effect of position around artificial weed on the average amount of herbicide per Petri dish collected from each wiper (mg a.i). Means followed by the same letter (in each column) are not significantly different (LSD, P< 0.05).

Position around artificial weed	Eliminator	Rotowiper	Weedswiper
1	1.99 **a**	5.09 **a**	0.16 **a**
2	0.43 **b**	1.34 **b**	0.07 **b**
3	0.03 **b**	0.25 **c**	0.05 **b**
4	0.03 **b**	0.03 **c**	0.04 **b**

6.3.4 Experiment 3b

Results from the field experiment with rushes using a Rotowiper at 5 km/hr showed that only a small fraction of dishes (2%) actually received any herbicide compared with the experiment with the artificial weeds. The two dishes that did receive some herbicide were placed directly in front of the rushes. The dishes for the untreated control that were placed 1m from the clumps did not receive any herbicide.

6.3.5 Experiment 3 c

More force was required for the sliding gate to pass over the clumps of rushes than was needed for the artificial weeds (Fig 6.6).

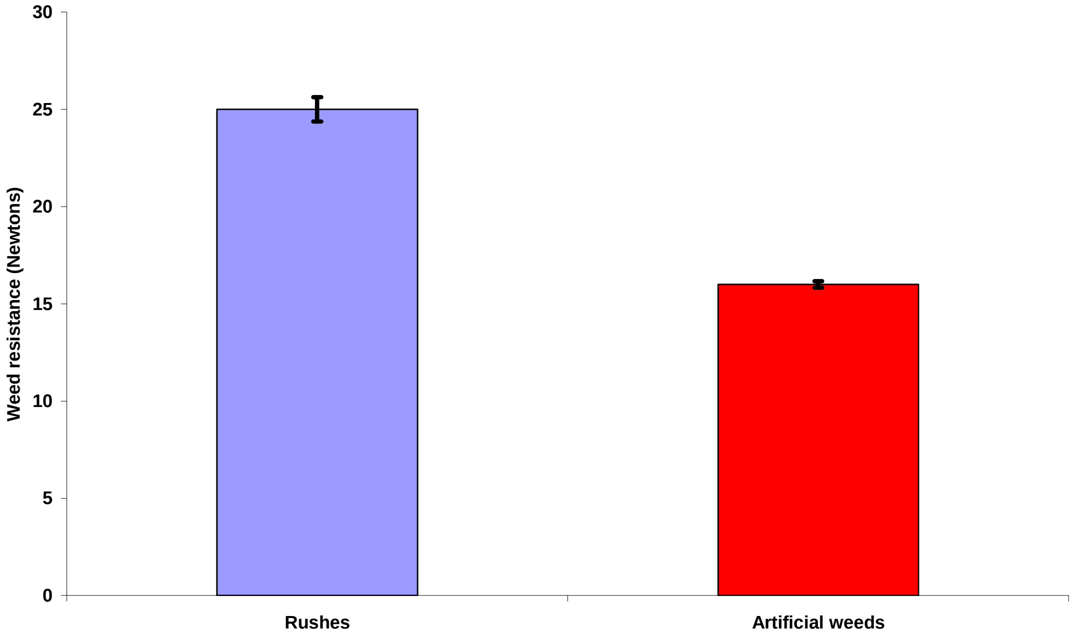


Fig 6.6 The amount of force (N) required to push the sliding gate over clumps of rushes and artificial weeds

6.3.6 Experiment 4

There was extensive damage to clover caused by herbicide being washed off the treated Californian thistle plants. All of the herbicides except glyphosate were washed off the Californian thistle plants in sufficient quantities to cause substantial damage to clover positioned under the plants (Fig 6.7). The clover was particularly damaged by clopyralid and metsulfuron washed off the thistle plants 1 day after application. Herbicide injury symptoms ranged from minor leaf discolouration to complete necrosis.

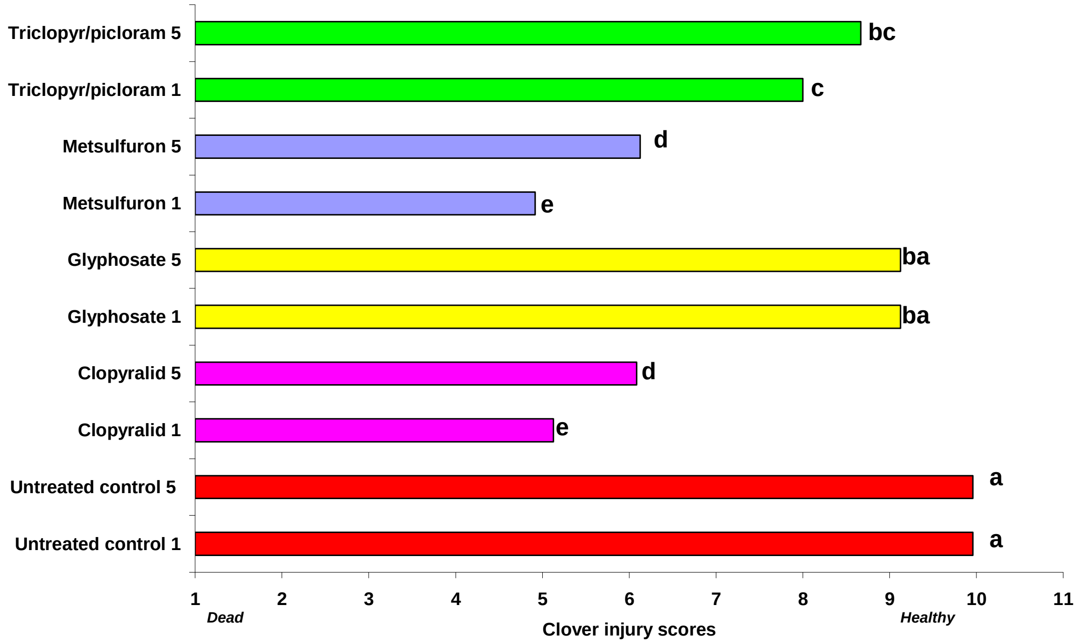


Fig 6.7 The severity of clover injury 20 days after simulated rainfall washed herbicide off Californian thistle plants on to the clover. Means with the same letter are not significantly different.

All the pots (100%) growing under clopyralid and metsulfuron-treated thistles washed after 1 day showed some herbicide injury (Fig 6.8). Glyphosate and triclopyr/picloram treatments had the least number of affected pots compared with other herbicide treatments.

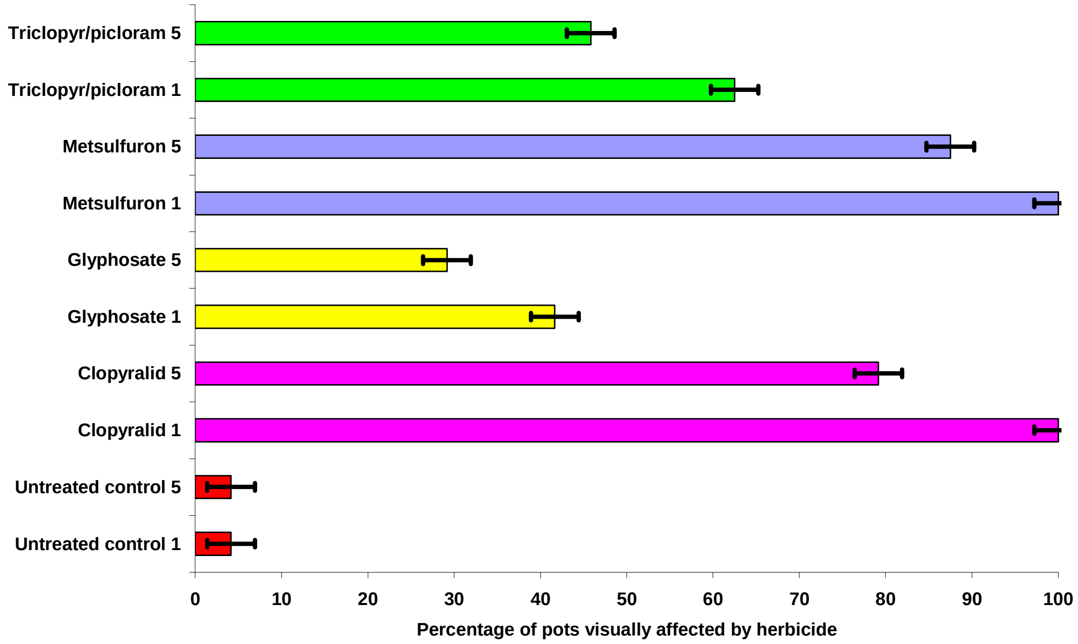


Fig 6.8 The proportion of white clover pots showing herbicide injury symptoms 20 days after simulated rainfall washed herbicide off Californian thistle plants on to the clover. (Vertical bars represent SEM, n=24).

Nine weeks after treatment when the plants were harvested, the herbicide damage to white clover measured at 20 days after glyphosate treatment was no longer evident. There was no difference between the dry weight of the clover from the two washing periods of Day 1 and Day 5, so the results for the two days were pooled together. Clopyralid, metsulfuron and triclopyr/picloram treatments were significantly different from the untreated control.

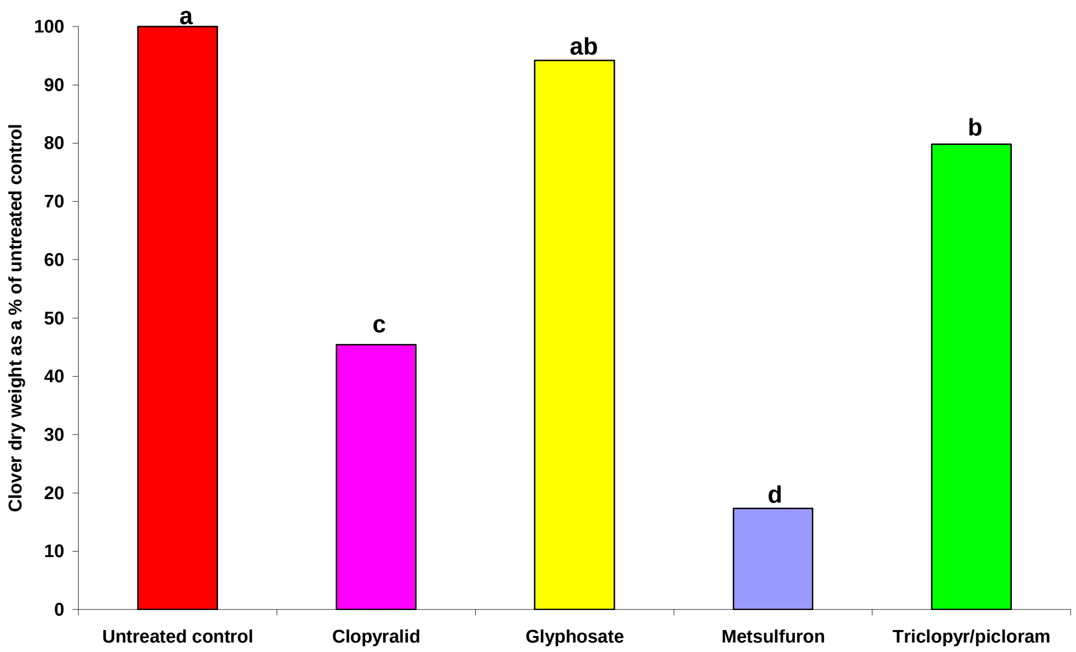


Fig 6.9 The dry weight of clover as a percentage of untreated control 9 weeks after simulated rainfall to wash herbicides off treated thistles. Means followed by the same letter are not significantly different (LSD, $P< 0.05$).

The metsulfuron washed off 1 day after application caused substantial damage to the ryegrass plants (Fig 6.10). Significantly less damage was caused overall when simulated rainfall occurred 5 days after herbicide application compared with 1 day (Fig 6.10). In contrast clopyralid, glyphosate and triclopyr/picloram caused no visible effects to the ryegrass.

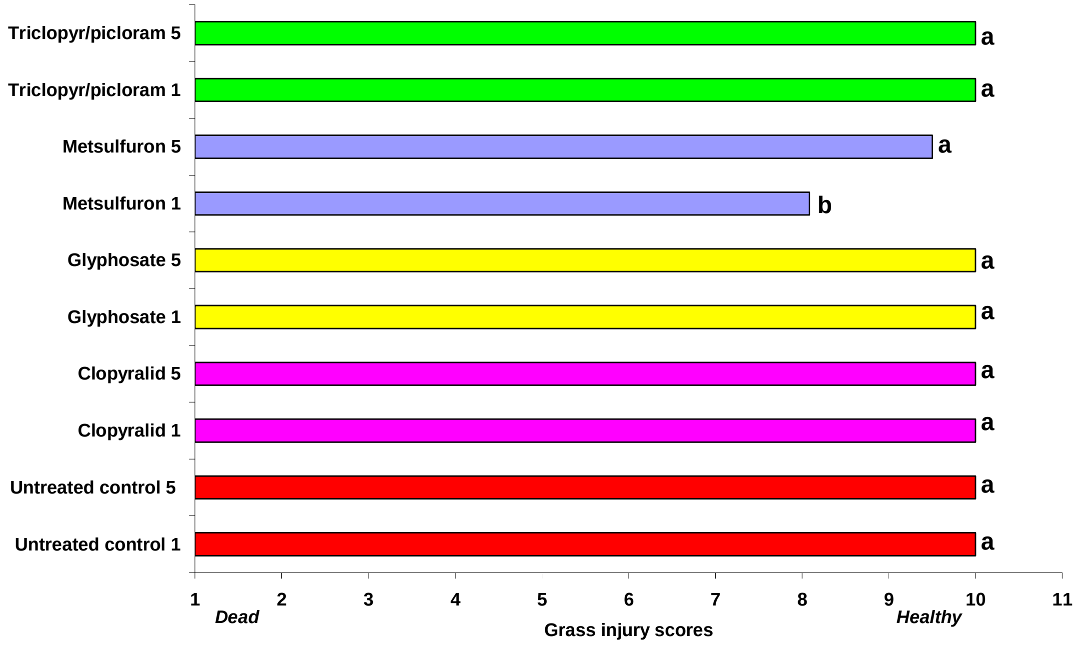


Fig 6.10 The severity of grass injury 20 days after simulated rainfall washed herbicide off Californian thistle plants on to the ryegrass. Means with the same letter are not significantly different.

There were more than twice as many pots that showed metsulfuron injury symptoms after rainfall was simulated after 1 day than after 5 days (Fig 6.11). All the other herbicides had no visual herbicide effect on the grass.

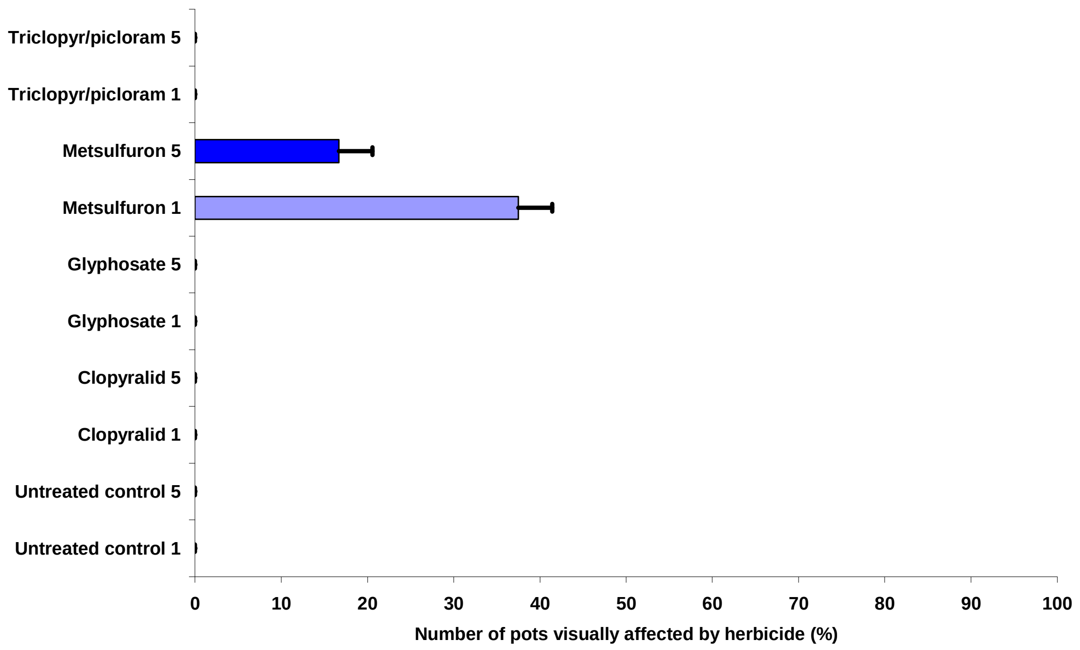


Fig 6.11 The proportion of ryegrass pots showing herbicide injury symptoms 20 days after simulated rainfall washed herbicide off Californian thistle plants on to the ryegrass. (Vertical bars represent SEM, n=24).

The effects of metsulfuron on ryegrass resulted in reduced dry weights at 9 weeks after treatment. None of the other herbicides had any effect on the dry weight of ryegrass (Fig 6.12).

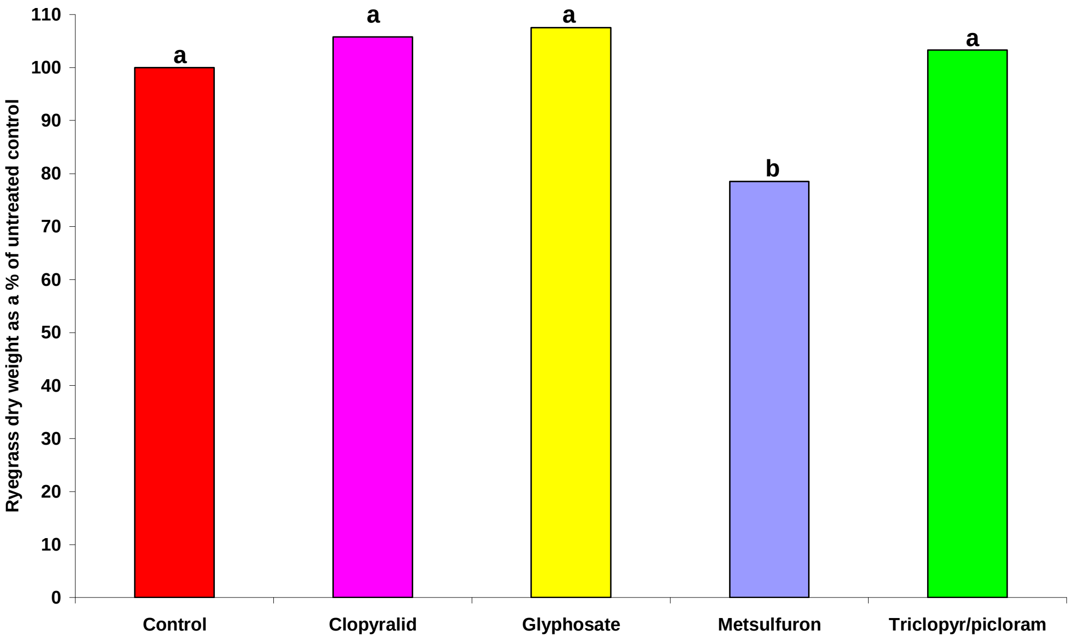


Fig 6.12 The dry weight of ryegrass 9 weeks after simulated rainfall to wash herbicides off from treated thistles. Means with the same letter are not significantly different.

Although the trial design involved blocking thistle plants according to plant size, there was no significant difference in damage to clover or ryegrass plants between the blocks.

6.4 Discussion

6.4.1 Rainfall

The widespread damage to pots under treated Californian thistles when rain was simulated showed that washing off of herbicides is the most likely cause of pasture damage. The results of this experiment confirm results from earlier weed-wiping studies in which damage was caused to plants by rainfall washing off herbicides away from the treated plants (Campbell & Nicol, 1998). The dry weights of clover exposed to glyphosate and triclopyr/picloram washed 5 days after wiping indicate that the injury was only transient with no effect on biomass 9 weeks after treatment presumably because less of these herbicides was washed off after 5 days than after 1 day.

Clopyralid and metsulfuron were the most damaging to clover while triclopyr/picloram and especially glyphosate were less damaging. The formulation of herbicides is important in determining the amount of damage. The ester formulation of triclopyr (Tordon Brushkiller) used in Experiment 4 was less damaging compared to the amine salt formulation (Tordon Gold) used in the field experiment (Chapter 5) possibly because of faster penetration and secondly because ester formulations are generally not easily washed off (Bovey & Diaz-Colon, 1969; Bovey et al., 1990). The oily nature of esters allows them to adhere to and penetrate plant tissues more readily than amines, and are therefore better in situations where rain is likely to occur soon after herbicide application since they resist being washed-off by rain (Zimdahl, 1999).

Metsulfuron, triclopyr and picloram were highly damaging to clover while the effect of glyphosate was minimal. These three herbicides are also known to be highly effective against white clover whereas glyphosate is known to be poor at controlling white clover. This lack of damage to clover by glyphosate confirms results from the field experiment and earlier studies by others (Makepeace & Thompson, 1982; Thompson, 1983; Grekul et al., 2005).

Metsulfuron, triclopyr and picloram are active in the soil which could partially explain the extent of the damage they caused to plants (Anderson, 1996; Zimdahl, 1999) whereas glyphosate is rapidly inactivated in the soil preventing any absorption of the herbicide by roots (Sprankle et al., 1975; Torstensson, 1985).

There was no damage to grass from any of the herbicides except metsulfuron. Clopyralid, triclopyr and picloram are known to have no effect on grasses while perennial ryegrass has partial tolerance to glyphosate at low rates. Although glyphosate is non-selective, its effect on ryegrass and clover was not as extensive as the damage caused by metsulfuron. This confirms earlier studies that showed that glyphosate at low rates can actually increase clover and ryegrass content of pastures (Casey et al., 2000).

The visual injury scores showed a significant difference in damage caused when rain was simulated on Day 1 compared with Day 5. This was probably because more of the herbicide had not been absorbed by plants after 1 day and was subsequently washed off causing more damage.

Results from the second and third field wiping studies (Chapter 5) did not show any pasture damage. It is important to highlight the differences between the two field experiments and the first trial in terms of rainfall amount, intensity and the time after application that rain fell (Table 5.5). In the first field experiment, there was 8.4 mm of rain falling three days after application followed by 3.2 mm the following day. It is likely sufficient herbicide was washed off to cause widespread damage. However, for the second field study, 5.2 mm of rain came 8 days after application for the early bud stage and only 0.2 mm of rain fell after 7 days for the early-post-flowering stage. The differences in intensity and distribution of rainfall can partly explain the differences in severity of pasture damage.

The delay in the onset of rainfall from the time of treatment explains lack of widespread damage to pasture in the second field trial with only metsulfuron having a significant effect. There was also very little damage in the late post-flowering application when rain fell from the day of application and for the next 12 days giving a total of 43.4 mm. It is likely that the high amount of rainfall would have diluted the herbicide thereby minimising the damage. The third field study did not show any pasture damage since rain only fell 9 days after treatment.

6.4.2 Splattering and dripping

The quantities of herbicide collected from Petri dishes around each of the artificial weeds showed significant differences between types of wiper, with the Rotowiper having the highest amount of herbicide collected and the Weedswiper having the least collected. The design of the wiper could be important in explaining this difference. The Eliminator consists of several wiper arms which come into contact with the weed and this can result in increased splattering compared to the Weedswiper. It is also possible that the Eliminator carries more loose liquid than the Weedswiper when saturated. The design of the wipers could also explain why the slower speed of the Eliminator resulted in more herbicide being collected than the faster speed while speed had no effect on the other two wipers.

There was also significantly more herbicide collected when the artificial weed structure was present than when absent. This suggests that generally minimal herbicide is lost just from the motion of the wiper under the conditions of this experiment. Some herbicide is released as a result of the interaction between the weed and the wiper with the herbicide flowing down the artificial weeds into Petri dishes.

The distribution of the herbicide collected suggests that most of the herbicide falls directly under the weed, possibly flowing down the stem. This fits with the localised damage noted at the base of plants in the field wiping experiment (Chapter 5) and similar trials (Martin et al., 1990). However, the amount of herbicide flowing down the stems of actual weeds in the field is likely to be restricted by branches of the weeds depending on the species involved.

The average quantity of clopyralid collected around each artificial weed was quite low with the highest from the Rotowiper being only 4 µg of the active ingredient per weed. The quantities of herbicide collected around each weed are unlikely to cause total removal of clover as in the field experiment. This is especially true with the Weedswiper where the highest average clopyralid collected per weed was only 0.08 µg of the active ingredient. The recommended rate for control of thistles is 300 g ai/ha (O'Connor, 2004). The herbicide picked up by the dishes from the different wipers translates to 0.5 g, 1.3 g and 0.1 g ai/ha for the Eliminator, Rotowiper and Weedswiper respectively. It is unlikely this would cause any damage to pasture.

The results from the field experiment with rushes are in contrast to the results with artificial weeds. Only two dishes out of a total of 100 had herbicide detected in them. Although the amount picked up by the dishes was small and none of the untreated control dishes picked up any herbicide, it can still be concluded that when a wiper hits a weed, some herbicide is lost to the ground. This result however is not surprising considering that the dishes were placed 15 cm from the clumps of rushes. Similarly, the dishes placed in position 3 and 4 in Experiment 4a did not receive much herbicide. This confirms that the herbicide is likely to reach pasture through flowing down the stems than splattering or the herbicide being flicked by the weeds.

The resistance of both artificial weeds and rushes to the motion of the wiper (Fig 6.6) can also explain the difference in the herbicide picked up in the Petri dishes. Although it would be expected that plants which offer more resistance to the wiper would squeeze out more herbicide from the carpet, results from this study showed more herbicide was picked up from artificial weeds which offered less resistance. It is therefore likely that several other factors besides resistance are also important. The way the artificial weeds spring up from underneath the wiper suggest that more herbicide is likely to be splattered around.

6.4.3 Exudation

There was some evidence that exudation of metsulfuron might contribute to pasture damage caused by wiper application of herbicides. However, any damage caused would be restricted to plants in the vicinity of target weeds. It appears likely that damage caused by exudation may have been accentuated in the experiment because roots were restricted to pots in which they were growing. Other studies have also concluded that unless a large amount of the root system of a companion crop comes into contact with roots of treated plants, herbicide release from treated plants seems unlikely to be important (Penn & Lynch, 1982). There is a need to further explore the role of exudation in causing pasture damage.

Although several studies have shown that herbicides are generally exuded in the rhizosphere (Coupland & Peabody, 1981; Gubbiga et al., 1996), it is possible exuded herbicide or their metabolites are not taken up by a nearby plant as demonstrated by Dinelli et al., (2007) working with diclofop-methyl and triasulfuron on durum wheat (*Triticum durum* Desf.) and Italian ryegrass (*Lolium multiflorum* Lam.)

There is no obvious reason to explain why metsulfuron damaged the clover in Experiment 2, yet triclopyr/picloram did not, unless metsulfuron is more easily exuded than triclopyr/picloram. Field results from wiper application of herbicides showed that metsulfuron and triclopyr/picloram both caused damage to pasture (Chapter 5). If exudation of herbicides was the primary cause, then both herbicides in Experiment 2 should have caused some damage to the clover growing with the thistles.

6.4.4 Translocation of herbicide from seed heads to daughter tillers

The visual scores and an actual count of necrotic tillers did not show any differences between the untreated control and the herbicide treatments although there was some limited herbicide activity. However, tiller death in treated plants was too minor to cause widespread damage to pasture as witnessed in the field wiping experiment. The results strongly suggest that damage is unlikely to be caused by translocation of herbicides to the daughter tillers. However, some studies with ^{14}C-labelled herbicides have shown a significant movement of herbicides together with photo-assimilates within grasses (Matthew, 2002). It is likely that translocation of herbicides to the daughter tillers in this study was partly limited by the stage of development of the seed-heads in each pot. There was a range of seed-head maturities in each pot at the time of treatment. The assimilate distribution and hence the movement of herbicide would have been influenced by the stage of development of each seed-head (Nyahoza et al., 1974). Seed-heads at grain-filling stage would have restricted movement of herbicide to the daughter tillers thereby reducing the risk of damage while translocation of herbicides to daughter tillers could have been enhanced in mature seed-heads.

6.5 Conclusions

The main conclusion from this study is that while translocation of herbicides from seed heads to daughter tillers, splattering and dripping are some of the means by which herbicides can be transferred from treated plants to pasture, the quantities are so tiny and any resultant damage (if any) is therefore likely to be minimal and highly localised. Root exudation and washing off by rain of herbicides from treated plants are the most likely cause of the damage. However, in terms of severity and distribution of the damage, rainfall seems to be the main cause. Despite the fact that rainfall is the main reason why pasture damage occurs from wiper application of herbicides, a huge knowledge gap still exists on the amount of rainfall that is likely to cause any damage. Too much rain is likely to dilute the effect of herbicides while too little rain is likely not to cause any damage. The time between herbicide application and onset of rainfall that will not result in pasture damage needs to be investigated further.

6.6 References

ANDERSON WP (1996) Weed Science: Principles and Applications. West Publishing Company. USA.

BONNET ME & BOSSCHAERT LM (1994) Glasshouse and field comparison of simulated rain on the activity of glyphosate. In: Comparing glasshouse and field pesticide performance II. Proceedings of an international symposium held at the University of Kent, Canterbury, 111-116.

BOVEY RW & DIAZ-COLON JD (1969) Effect of simulated rainfall on herbicide performance. *Weed Science* **17**, 154-157.

BOVEY RW, MEYER RE & WHISENANT SG (1990) Effective simulated rainfall on herbicide performance in huisache (*Acacia farnesiana*) and honey mesquite (*Prosopis glandulosa*). *Weed Technology* **4**, 26-30.

BRYSON CT (1987) Effects of rainfall on foliar herbicides applied to rhizome Johnsongrass. *Weed Science* **35**, 115-119.

CAMPBELL MH & NICOL HI (1998) Effects of wiping herbicides on serrated tussock (*Nassella trichotoma* (Nees) Arech.) and African lovegrass (*Eragrostis curvula* (Shrad.) Nees). *Plant Protection Quarterly* **13**, 36-38.

CASEY MJ, BROWN C & STEVENS DR (2000) A summary of research into the use of low rates of glyphosate as a pasture management tool. In: *Proceedings of the New Zealand Grassland Association* **62**, 123-128.

COUPLAND D & CASELEY JC (1979) Presence of 14C activity in root exudates and guttation fluid from *Agropyron repens* treated with 14C-labelled glyphosate. *New Phytologist* **83**, 17-22.

COUPLAND D & PEABODY DW (1981) Absorption, translocation and exudation of glyphosate, fosamine and amitrole in field horsetail (*Equisetum arvense*). *Weed Science* **29**, 556-560.

DINELLI G, BONETTI A, MAROTTI I et al. (2007) Root exudation of diclofop-methyl and triasulfuron from foliar-treated durum wheat and ryegrass. *Weed Research* **47**, 25-33.

FICK WH & MOSER LE (1978) Carbon-14 translocation in three warm-season grasses as affected by stage of development. *Journal of Range Management* **31**, 305-308.

FORDE BJ (1966) Translocation in grasses. 1. Bermuda grass. 2. Perennial ryegrass and couch grass. *New Zealand Journal of Botany* **4**, 479-514.

GERBER HR, NYFFELER A & GREEN DH (1983) The influence of rainfall, temperature, humidity and light on soil and foliage-applied herbicides. *Aspects of Applied Biology*, 1-14.

GREKUL CW, COLE DE & BORK EW (2005) Canada thistle (*Cirsium arvense*) and pasture forage responses to wiping with various herbicides. *Weed Technology* **19**, 298-306.

GUBBIGA NG, WORSHAM AD & CORBIN FT (1996) Root/rhizome exudation of nicosulfuron from treated Johnsongrass (*Sorghum halepense*) and possible implications for corn (*Zea mays*). *Weed Science* **44**, 455-460.

HALE MG, FOY CL & SHAY FJ (1971) Factors affecting root exudation. *Advances in Agronomy* **23**, 89-109.

HICKMAN MV, MESSERSMITH CG & LYM RG (1990) Picloram release from leafy spurge roots. *Journal of Range Management* **43**, 442-445.

HURTT W & FOY CL (1965) Excretion of foliar-applied dicamba and picloram from roots of valentine peas grown in soil, sand, and culture solution. In: *Northeast Weed Control Conference,* **19**, 602.

LINDER PJ, CRAIG JC, COOPER FE & MITCHELL JW (1958) Movement of 2,3,6-trichlorobenzoic acid from one plant to another through their root systems. *Journal of Agricultural and Food Chemistry* **6**, 356-357.

LINDER PJ, MITCHELL JW & FREEMAN GD (1964) Persistence and translocation of exogenous regulating compounds that exude from roots. *Journal of Agricultural and Food Chemistry* **12**, 437-438.

MAKEPEACE W & THOMPSON A (1982) Ragwort control using a rope wick applicator. In: *Proceedings 1982 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 256-260.

MARTIN P, FULLERTON DK & JAMES TK (1990) Weed trials using a rotary weed wiper. In: *Proceedings 1990 New Zealand Weed and Pest Control Conference,* Dunedin, New Zealand, 262-265.

MATTHEW C (2002) Translocation from flowering to daughter tillers in perennial ryegrass (*Lolium perenne* L.). *Australian Journal of Agricultural Research* **53**, 21-28.

MESSERSMITH CG & LYM RG (1985) Roller application of picloram for leafy spurge control in pastures. *Weed Science* **34**, 8-12.

MILLER DK, GRIFFIN JL & RICHARD EP, JR. (1998) Johnsongrass (*Sorghum halepense*) control and rainfastness with glyphosate and adjuvants. *Weed Technology* **12**, 617-622.

MOUNTIER NJ & RADCLIFFE JE (1965) Problems in measuring pasture composition in the field. Observer variation with the point method. *New Zealand Journal of Botany* **3**, 243-252.

NYAHOZA F, MARSHALL C & SAGAR GR (1974) Assimilate distribution in *Poa pratensis* L.: a quantitative study. *Weed Research* **14**, 251-256.

O'CONNOR B (2004) Novachem Manual 2004/2005. In: *Novachem Manual* (Novachem Services Limited), Palmerston North 488 pp.

O'SULLIVAN PA & KOSSATZ VC (1984) Absorption and translocation of 14C-3,6-dichloropicolinic acid in *Cirsium arvense* (L.) Scop. *Weed Research,* **24**, 17-22.

PENN DJ & LYNCH JM (1982) Toxicity of glyphosate applied to roots of barley seedlings. *New Phytologist* **90**, 51-55.

PENNER D (2000) Activator adjuvants. *Weed Technology* **14**, 785-791.

ROTOWORKS (2007) Rotowiper. [Online]: Available: http://www.rotowiper.co.nz/Using.htm [Retrieved 21 August 2007].

ROVIRA AD (1969) Plant root exudates. *Botanical Review* **35**, 35-57.

SAS INSTITUTE (2004) Statistical Analysis System. SAS version 9.1.

SCHULTZ ME & BURNSIDE OC (1979) Absorption, translocation and metabolism of 14C-2,4-D and 14C-glyphosate by hemp dogbane (*Apocynum cannabinum* L.). In: *Abstracts of 1979 Meeting of the Weed Science Society of America,* 95-96.

SPRANKLE P, MEGGITT WF & PENNER D (1975) Rapid inactivation of glyphosate in the soil. *Weed Science* **23**, 224-228.

THOMPSON A (1983) Pasture weed control by rope wick applicator. In: *Proceedings 1983 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 96-98.

TOMLIN CDS (2000) The Pesticide Manual. In: *A World Compendium* (1250. British Crop Protection Council, Surrey, UK.

TORSTENSSON L (1985) Behaviour of glyphosate in soils and its degradation. In: *The herbicide glyphosate* (eds E Grossbard & D Atkinson), 137-150. Butterworth, London.

VANDEN BORN WH (1969) Picloram residues and crop production. *Canadian Journal of Plant Science* **49**, 628-629.

ZIMDAHL RL (1999) Fundamentals of weed science. Academic Press, San Diego.

Chapter 7

7 A spectrophotometric technique for measuring herbicide deposition on weeds from wiper applicators

7.1 Introduction

Herbicide wipers apply concentrated herbicide solution directly onto the foliage and stems of weeds (Dale, 1978; McWhorter & Derting, 1985). This ensures precision application of highly effective translocated herbicides with minimal damage to pastures or desired crops (Lutman et al., 1982; Makepeace & Thompson, 1982; Mayeux & Crane, 1985; Martin et al., 1990). No droplets are formed and drift problems are thus eliminated. Application of herbicides with wipers is known as an efficient technique with herbicide savings of up to 80% compared to broadcast spraying (Schepers & Burnside, 1979).

In New Zealand, there are a number of commercially available applicators including the Eliminator, Rotowiper and Weedswiper. The design of these three wiper applicators is described in Chapter 2. These wipers have achieved good control of Californian thistles in the field (Chapter 5; Grekul et al., 2005), but some studies have reported variable performance (Furrer et al., 1980; Meeklah & Mitchell, 1984; Martin et al., 1990). Little research has been conducted to evaluate the performance of the applicators currently available on the market. To study factors affecting wiper effectiveness, techniques are required to accurately measure the amount of herbicide deposition on to weeds from wipers.

Current recommended application rates for the three wipers are the same (O’Connor, 2004), despite differing output from these wipers. Various experiments have attempted to calculate the quantity of chemicals wiped on to weeds. Some researchers have used techniques in which fluorescent dyes are added to a herbicide solution and then the sprayed herbicide is recovered by washing it with a solvent, followed by analysis with a fluorometer. The concentration of the herbicide is then indirectly estimated by the fluorescence of the dye (Sharp, 1974; Richardson, 1984). However, this technique does not offer a direct measurement of the actual herbicide but rather the fluorescence of a dye mixed with it. Problems were also discovered with fluorescent substances breaking down on exposure to sunlight (Richardson, 1984) and the herbicide contributing to the fluorescence (Sharp, 1976).

Another technique that has been used involves measuring pre and post-application volume in the wiper reservoir. The amount of herbicide used is divided by the area covered in the trial to calculate the application rate per area and by the number of plants to calculate the dose per weed (Mayeux, 1987; van Toor et al., 1994). This technique is not very precise, as it does not take into account the herbicide lost through splattering and dripping.

Other researchers have tried to measure output of these wipers by polarography (voltammetry). Glyphosate deposited on plants was measured by washing treated plants within 30 minutes of application, with the subsequent solution analysed using a polarographic analyser in which the concentration of a solution is measured in relation to the electric current passing through it (Lutman et al., 1982).

The objective of the experiments described in this study was to develop a simpler, more direct method of measuring the volume of herbicides wiped onto weeds using an ultraviolet (UV) visible spectrophotometer. The spectrophotometer measures the intensity of radiation absorbed by a solution at different wavelengths by looking at its transmittance or emissions (Thompson, 2006). The amount of radiation absorbed is directly related to the concentration of the substance. The Beer-Lambert Law provides the mathematical basis of the relationship between concentration of a solution and its absorbance (Lykos, 1992). According to the Beer-Lambert Law, an increase in the concentration of a compound leads to a linear increase in the absorbance of the solution (Ricci et al., 1994).

Once this technique was developed, a second objective was to use it to evaluate the performance of three wiper applicators at different speeds and moisture levels to determine their optimum performance.

7.2 Method and Materials

7.2.1 Preliminary experiments: construction of a standard curve

The suitability of three herbicides for use with the spectrophotometer was investigated. A preliminary test determined the absorption spectrum of clopyralid, glyphosate, and metsulfuron. Clopyralid was chosen as the most suitable of the three herbicides as it formed clearly visible absorption peaks and could be detected at dilution rates of up to 1:15,000 (herbicide: water).

The absorbance was measured using a Hitachi Model U2000 UV–VIS spectrophotometer for two wavelengths (λ_{221} nm and λ_{280} nm) where the absorbance levels were at their peak. Absorbance for the λ_{280} nm peak was used in all calculations since it was more stable at very low concentrations than at the λ_{221} nm peak. A calibration (standard) curve was then constructed by recording the absorbance of clopyralid solutions with a known concentration. These known concentrations are referred to as standard solutions. The standard curve was then used to quantify the concentration of unknown herbicide solutions.

A (300 mg ai per litre) herbicide stock solution was prepared by adding 1 ml herbicide product to 1L of water. Seven herbicide solutions were then prepared from the stock solution by means of two-fold serial dilutions whereby each sample was half as concentrated as the previous sample and each solution was made from the previous sample. The dilutions were made in such a way that the same volume of herbicide solution was added to the same volume of distilled water at each step as this repeatable pattern was thought to be most efficient and less subject to error than using different volumes at each step.

Once all the standard solutions had been prepared, they were analysed in the spectrophotometer beginning with the most dilute solution. The absorbance of the standard solutions (replicated three times) was then plotted as log concentration vs. log absorbance to create a standard curve working from dilute to concentrated samples to reduce error due to contamination. Once a standard curve was prepared, it was then possible to determine the concentration of an unknown solution using the standard curve or by its equation calculated using linear regression (Fig 7.1). A new standard curve was constructed each time a new experiment was run using the same herbicide solution. The seven dilutions demonstrated a strong linear relationship as illustrated by an r^2 value of 0.999 (Fig 7.1) and therefore deemed suitable for determination of the concentrations of unknown samples.

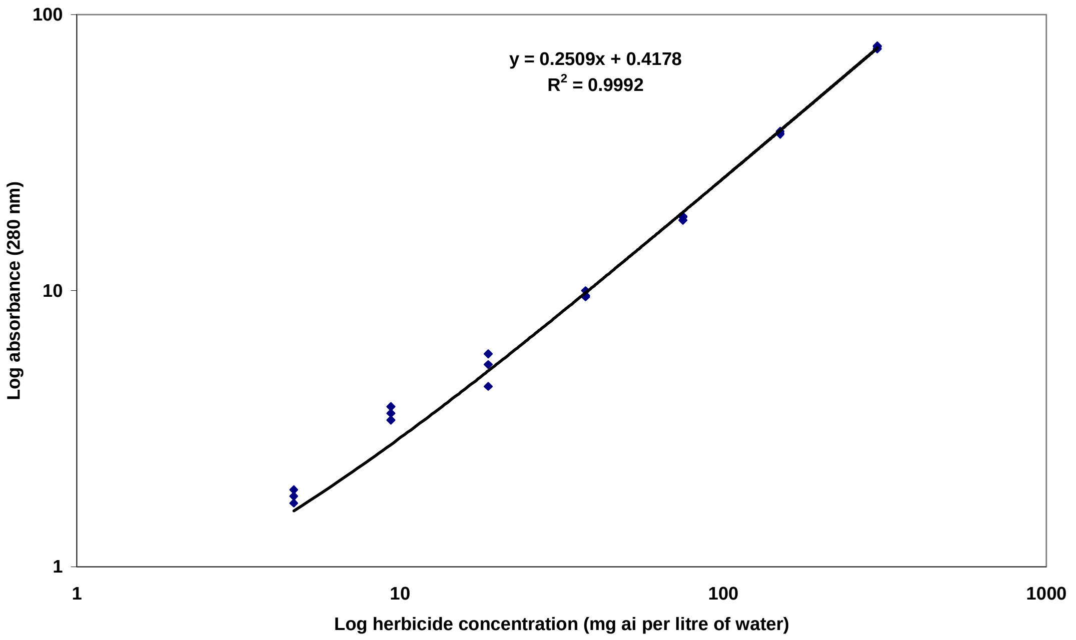


Fig 7.1 A standard curve showing the relationship between the concentration of clopyralid and its absorbance at 280 nm using a UV–VIS spectrophotometer

7.2.1.1 Deposition of clopyralid on non-absorbent surfaces

The technique was tested by spreading 0.5 ml of 2.5% (1 ml herbicide: 39 ml water) solution of herbicide on non-absorbent PVC strips (50 cm x 3 cm), then washing them with a 250 ml of water and analysing samples of the resultant solution in the spectrophotometer. The strips were washed after either 10 minutes or 30 minutes.

7.2.1.2 Deposition of clopyralid on rushes

The technique was also tested on small clumps of rushes (15 stems/clump) using the same dilution rates as for non-absorbent PVC strips, washing them with 250 ml of water and analysing a sample of the resultant solution in the spectrophotometer. The clumps of rushes were collected from the field at Massey University and tested in the laboratory. The stock solution used to construct a standard curve came from washing untreated rushes to take into account the effect on absorbance of chlorophyll or other compounds washed off from the rushes. The rushes were washed after either 10 minutes or 30 minutes.

7.2.2 Experiment 1

Experiment 1 investigated the effect of wetness of the wiper pads on herbicide output from the Eliminator. The experiment was carried out in September 2005 on asphalt pavement using an artificial weed structure. The artificial weed structure is described in Chapter 6. The “weeds” were covered in plastic sleeves folded at the base to collect drips while the three wipers were driven over the “weeds” (Plate 7.1). The sleeves were 15 cm wide and 70 cm long although the bottom 5 cm was folded up to collect any drips. Rubber bands were used to keep the plastic sleeves in position while the wipers were being driven over the “weeds”.

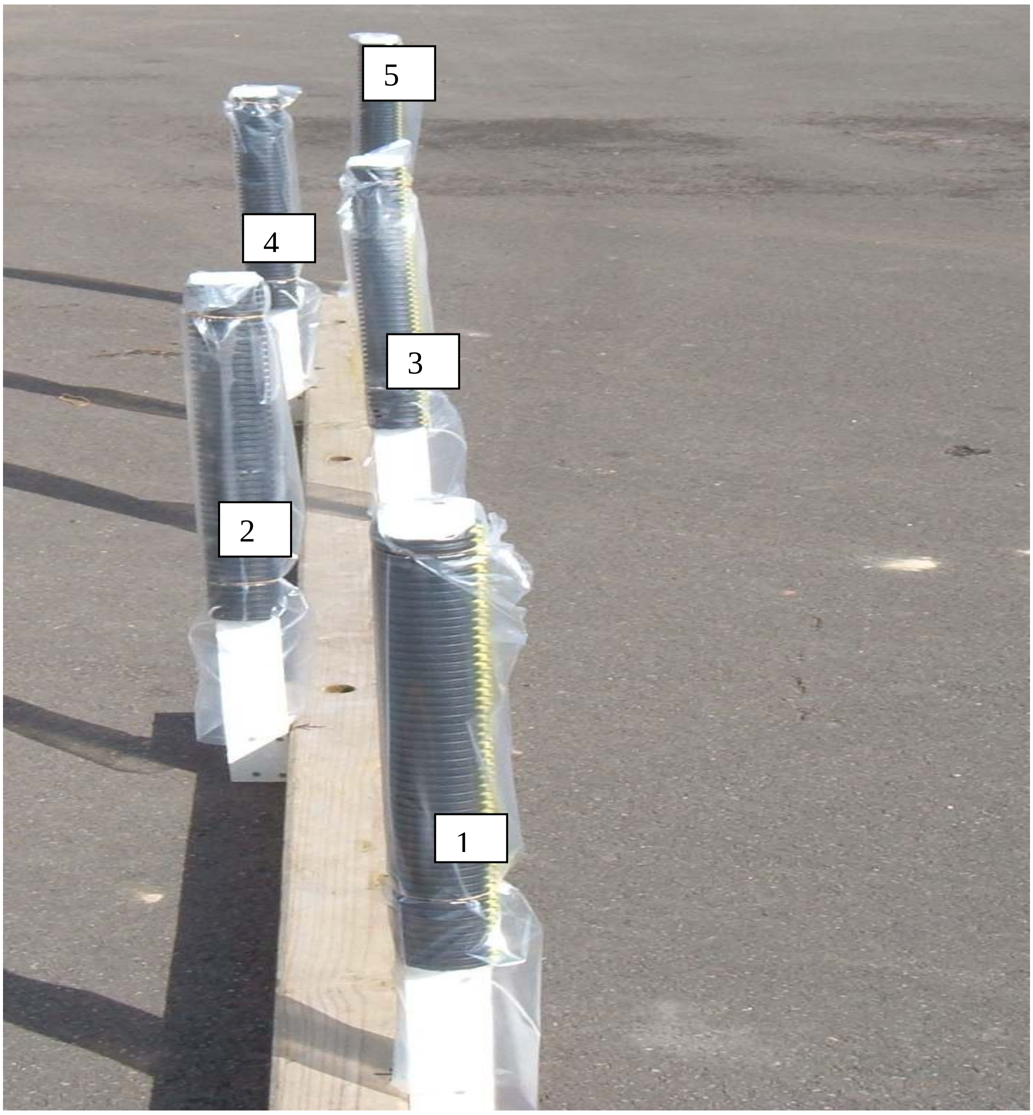


Plate 7.1 Artificial weed structure showing weed positions (1-5) covered in plastic sleeves

Clopyralid was used in this experiment at the same concentration as used in preliminary experiments (Section 7.2.1.1), though a new standard was produced using this new batch of herbicide solution.

The direction of travel was from weed in Position 1 to Position 5 (Plate 7.1). Since the weeds were offset on each side of the supporting beam, weeds in Positions 1, 3 and 5 (same row) were likely to be hit from the same point of the wiper while “weeds” in Position 2 and 4 (same row) were likely to be hit from a different position.

Three moisture levels for the weed wipers were investigated. The levels were defined as low, medium and high. A low moisture level was defined as being moist but two fingers could be firmly pressed against the pads without causing dripping. The medium moisture level was defined as being moist enough after firm pressure by two fingers would form one or two drops. The high moisture level was achieved by turning on the pump until the pads started dripping. The wiper was then allowed to stand until the dripping stopped. Treatment followed immediately after the dripping stopped. Pressing the pad at that stage resulted in a continuous flow of herbicide to the ground. To avoid the pad becoming too wet the low moisture level treatments were done first followed by the medium level and finally the high moisture level.

After the wipers were driven over the “weeds”, the sleeves were removed and sealed in bags and stored in a cold room at 4^0C before analysis with the spectrophotometer. Storage was necessary as the number of sleeves could not be processed in a single day. A preliminary test had shown that storing the bags would not affect the herbicide quantity or concentration. The treated bags were then washed with 250 ml of water and three samples from each resultant solution were analysed using the spectrophotometer.

The quantity of herbicide deposited on the artificial weeds at each moisture level was measured at 5 km/hr and 10 km/hr for each treatment. The experiment had a factorial design with one wiper, two speed levels and three saturation levels replicated three times to give a total of 18 runs over the five artificial weeds. An analysis of variance (ANOVA) of herbicide deposits was carried out using the statistical software package SAS (SAS Institute, 2004).

7.2.3 Experiment 2

Experiment 2 investigated the relationship between speed of the three wipers and herbicide output. The same herbicide solution used in Experiment 1 was applied to the artificial weeds described earlier. For the Rotowiper, a detergent (Sunlight Liquid) was added at a rate of 1L/45 L water as recommended by the manufacturers (Rotoworks, 2007). The detergent was added to create foam on the carpet to assist with estimating the wetness of the wiper. A standard curve constructed with the detergent was not different from the one constructed without the detergent. The experiment was done in February 2006.

The three wipers were used at their maximum moisture level. The Rotowiper and the Eliminator were towed by a quad bike while the Weedswiper was mounted on the back of a tractor.

For each run, a timer was used to calculate the speed of the wiper. A series of 16 different speeds was used for each wiper. The speed range for the Eliminator was 4.3 km/hr - 12.2 km/hr, while that for the Rotowiper was 4.9 km/hr - 10.3 km/hr and that for the Weedswiper was 4.8 km/hr - 10.1 km/hr. A linear regression between the speed of each applicator and the volume of herbicide deposited on the artificial weeds was calculated using SAS (SAS Institute, 2004).

7.2.4 Experiment 3

Experiment 3 compared the herbicide output of the three wipers at a constant speed of 5 km/hr for all wipers. The experiment was otherwise performed exactly as in Experiment 2 with a constant speed replicated five times. The experiment was done in August 2006. An ANOVA of herbicide output was conducted using the statistical software package SAS (SAS Institute, 2004).

7.3 Results

7.3.1 PVC strips

The herbicide recovery rate was above 98% both at 10 minutes and 30 minutes, respectively (Fig 7.2). There was no difference in the recovery rates for the two periods. Once the test proved successful, it was then used to measure deposition of herbicide on artificial weed structure simulating weeds.

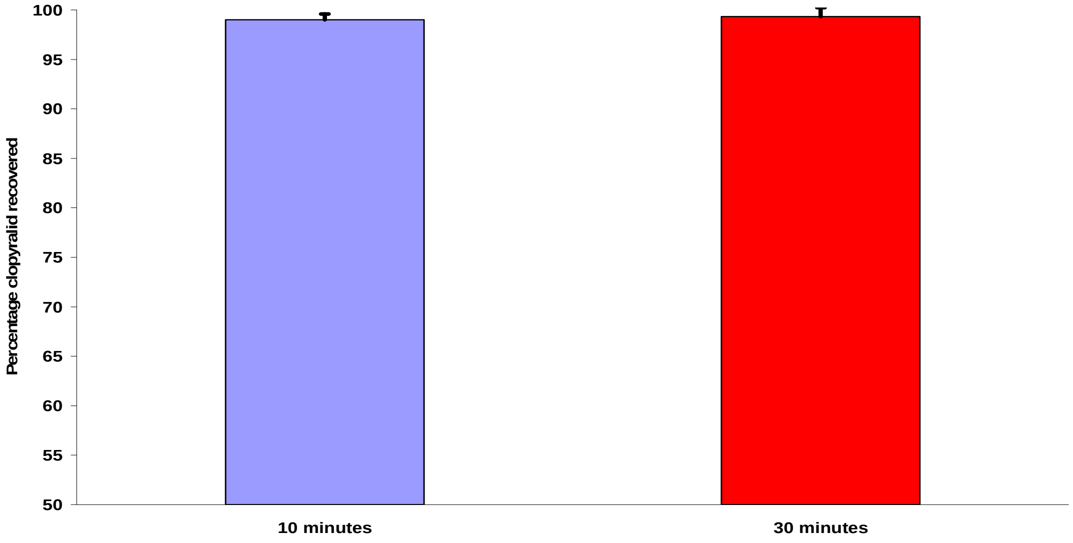


Fig 7.2 The proportion of clopyralid recovered from non-absorbent PVC strips after 10 and 30 minutes. (Vertical bars represent SEM, n=9).

7.3.2 Rushes

The average recovery rate of the herbicide after 10 minutes was 98% while the recovery rate after 30 minutes was 78% (Fig 7.3).

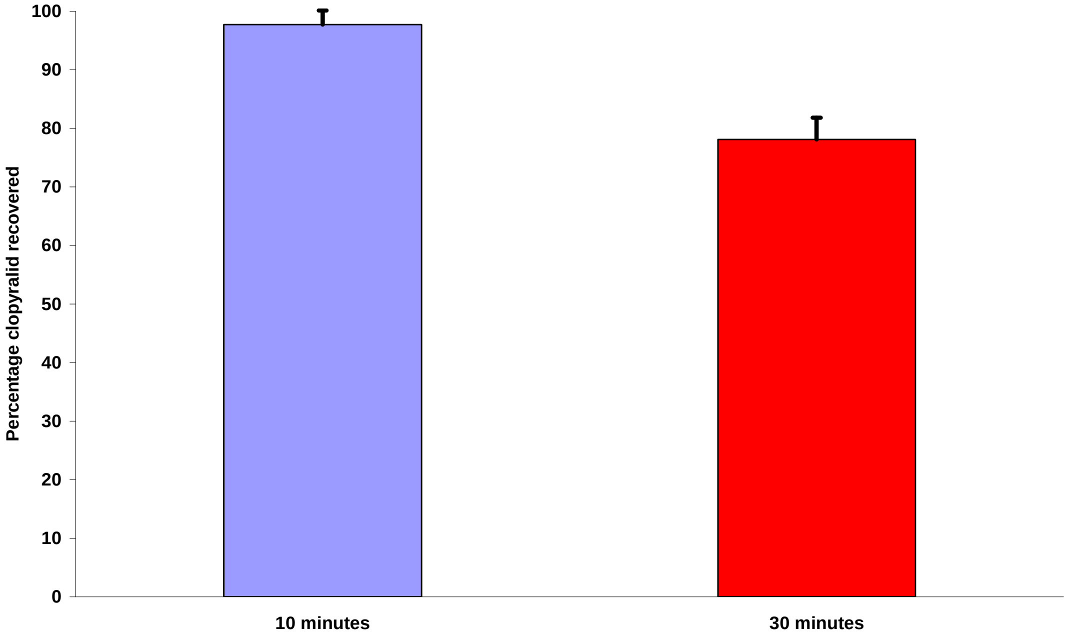


Fig 7.3 The proportion of applied clopyralid recovered from rushes after 10 and 30 minutes. (Vertical bars represent SEM, n=9).

7.3.3 Experiment 1

As expected, the quantity of herbicide deposited on the artificial weeds was strongly dependent on the moisture level of the wiper. The highest moisture level deposited the highest quantity of herbicide while the lowest moisture level deposited only 32% as much as the wettest treatment (Fig 7.4). The lowest moisture level also deposited only 48% of the medium moisture level. The speed of the wiper had no effect on the quantity of herbicide deposited despite one treatment being twice the speed of the other treatment.

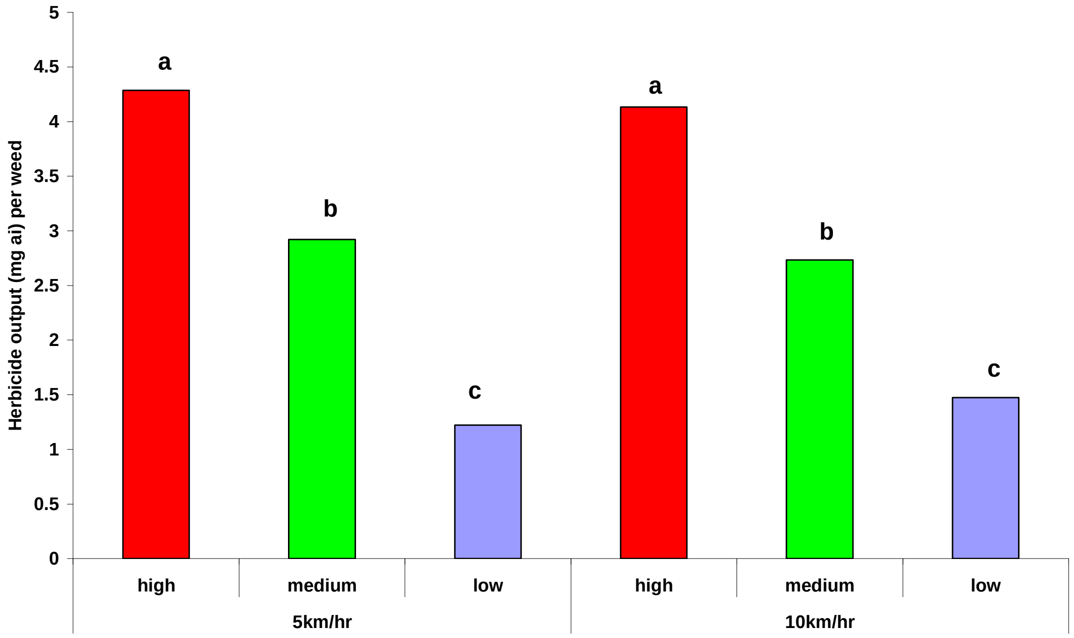


Fig 7.4 The quantity of clopyralid deposited on artificial weeds by the Eliminator at different moisture levels (low, medium and high) and two speeds (5 & 10 km/hr). Means followed by the same letter are not significantly different (LSD, $P< 0.05$).

The average quantity of clopyralid deposited on individual artificial weeds varied depending on the weed position. Although there were some differences between weed positions, there was no consistent trend from Position 1 to Position 5 (Table 7.1).

Table 7.1 The effect of weed position on the average amount of herbicide (mg ai) collected per "weed" at different moisture levels (low, medium and high). Means followed by the same letter (in each column) are not significantly different (LSD, P< 0.05). (Weeds 1, 3 & 5 were in the same path of the wiper while 2 & 4 were in another path).

	Moisture level		
Weed position	**High**	**Medium**	**Low**
1	5.4 **a**	3.5 **a**	2.0 **a**
2	4.7 **ab**	3.4 **ab**	1.2 **ab**
3	4.2 **ab**	1.8 **c**	1.9 **a**
4	3.9 **b**	2.3 **bc**	0.5 **b**
5	3.5 **b**	2.8 **ab**	1.6 **ab**

7.3.4 Experiment 2

This experiment also showed there was no relationship between the speed of the wipers and their herbicide output (Figs 7.5-7.7). Although the effect of speed was not significant, the output from the Eliminator was significantly higher than that of the Rotowiper and Weedswiper. The data were extremely variable, especially for the Rotowiper but less so for the Weedswiper, and this means any trend would not have been detected.

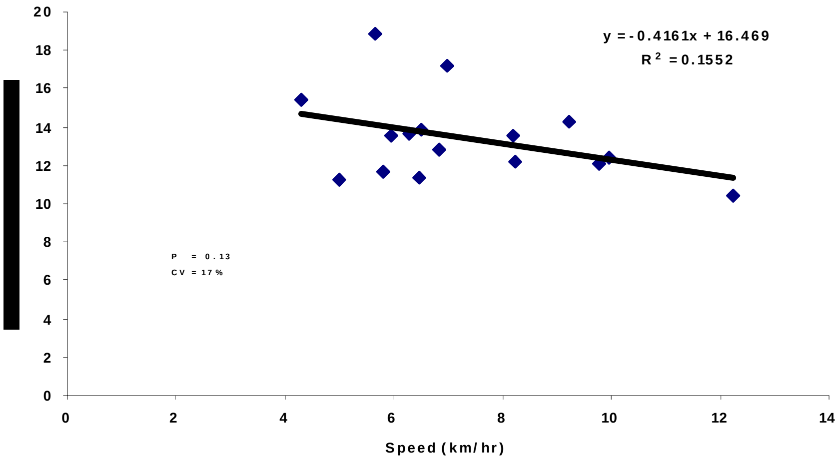


Fig 7.5 The quantity of clopyralid deposited on artificial weeds by the Eliminator at different speed levels. P= 0.13. The Co-efficient of variation (CV) = 17%.

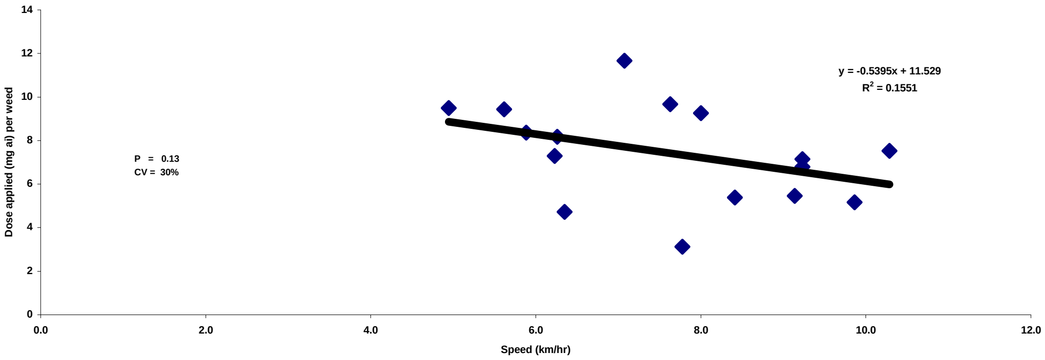


Fig 7.6 The quantity of clopyralid deposited on artificial weeds by the Rotowiper at different speed levels. P= 0.13. CV =30%.

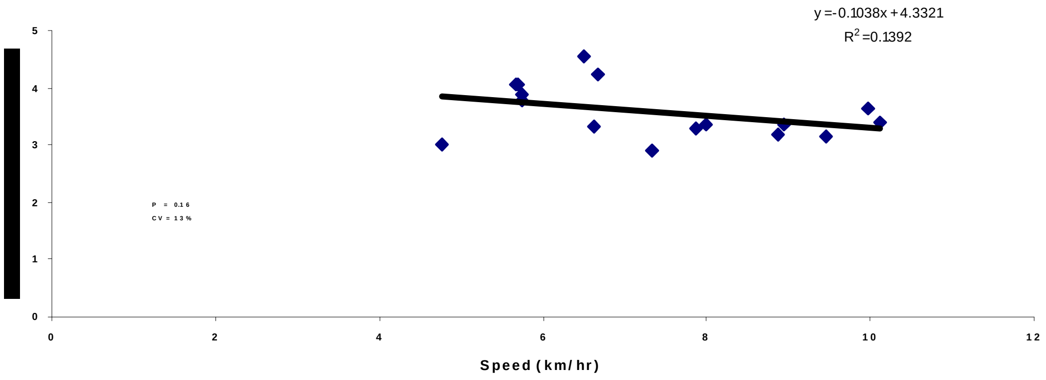


Fig 7.7 The quantity of clopyralid deposited on artificial weeds by the Weedswiper at different speed levels. P= 0.16. CV = 13%.

7.3.5 Experiment 3

At a constant speed of 5 km/hr for all three wipers, the Rotowiper had the highest output while the Weedswiper had the least (Fig 7.8). The Eliminator was intermediate in performance. The Weedswiper, however, had the most uniform output across all weed positions while the deposits from the Eliminator and Rotowiper showed a high variability (Figs 7.5-7.7). However, there was huge variability in the data for single weed positions. The variability was so large that for the Eliminator, there was a 9-fold difference between the smallest and highest herbicide deposit on the weeds while there was a 3-fold and 6.5-fold difference for both the Weedswiper and Rotowiper, respectively.

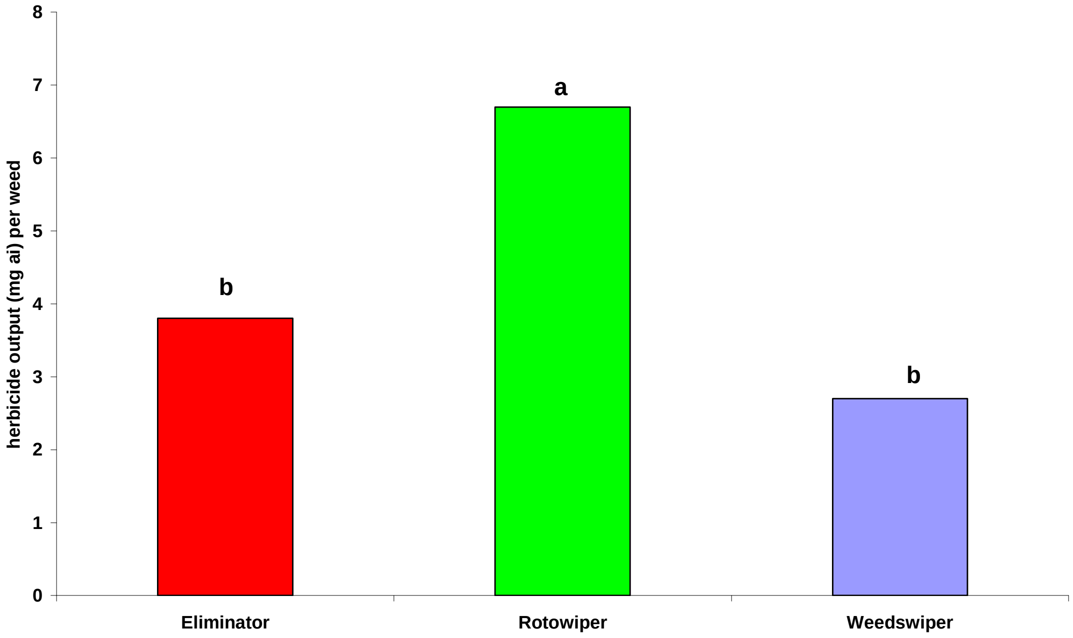


Fig 7.8 The quantity of clopyralid deposited on artificial weeds by wiper applicators at 5 km/hr. Means followed by the same letter are not significantly different (LSD, P< 0.05).

There was no significant decrease in the amount of herbicide deposited by all three wipers from the first to the last weed (Figs 7.9-7.11).

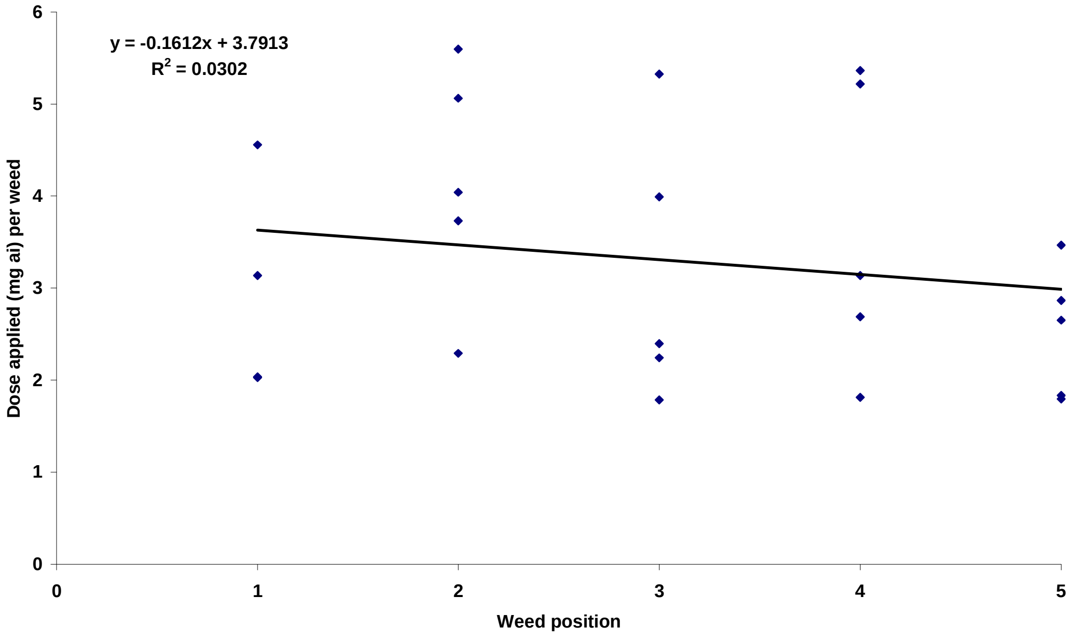


Fig 7.9 The amount of clopyralid deposited at different weed positions by the Eliminator at 5 km/hr.

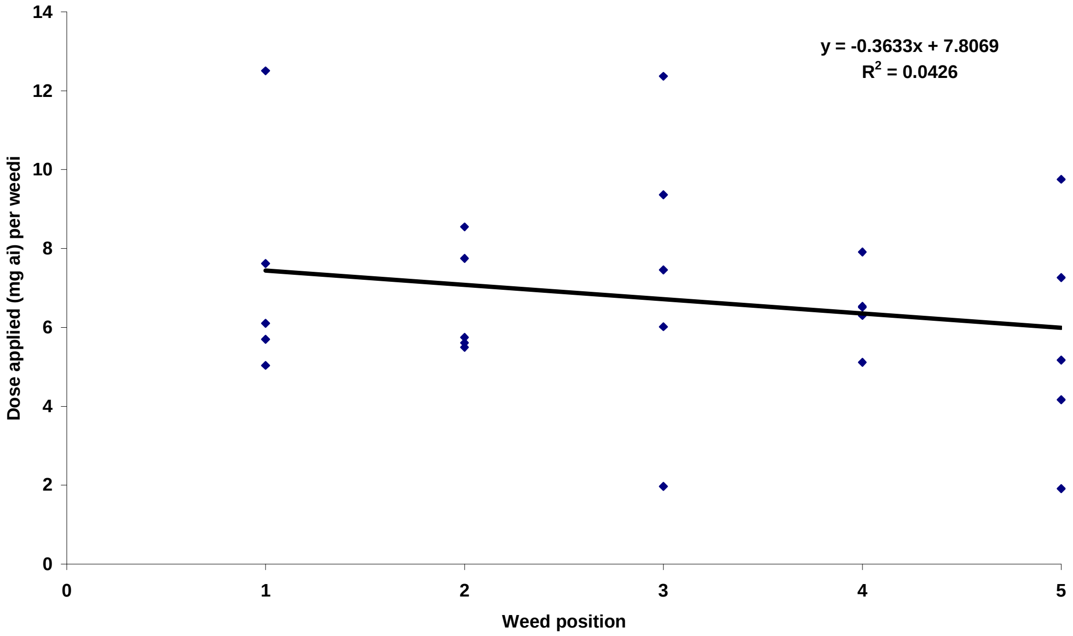


Fig 7.10 The amount of clopyralid deposited at different weed positions by the Rotowiper at 5 km/hr.

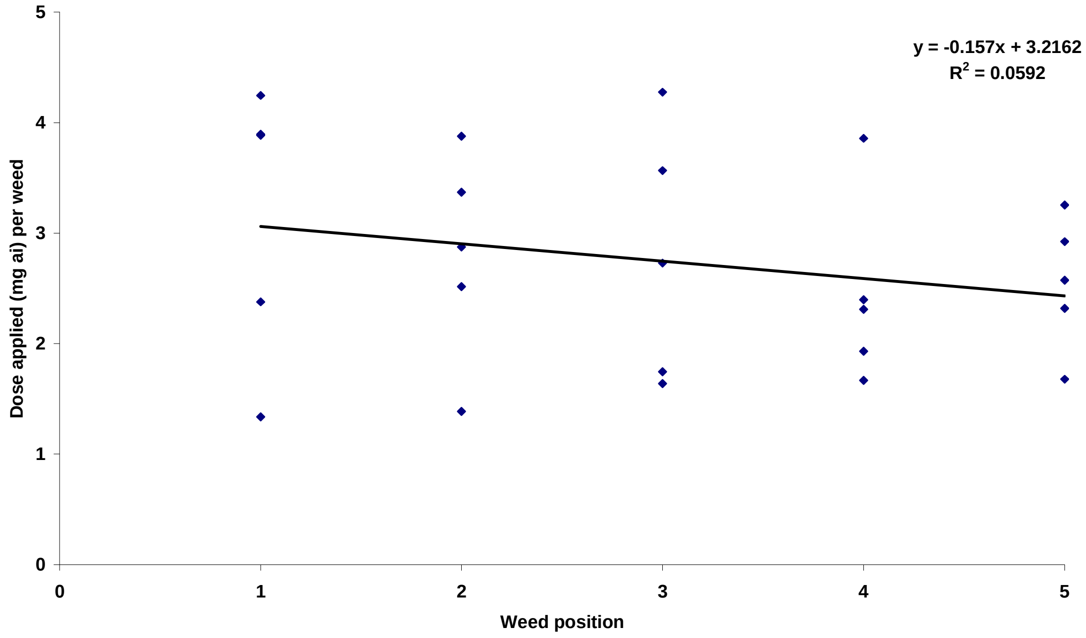


Fig 7.11 The amount of clopyralid deposited at different weed positions by the Weedswiper at 5 km/hr.

7.4 Discussion

The spectrophotometric technique provided a direct and reliable means of measuring herbicide output from weed wipers. Repeated tests using known herbicide concentrations showed this technique to be precise and consistent with a high recovery rate of applied herbicides.

The ability of the spectrophotometer to detect herbicides at very low concentrations makes it a powerful research tool in studying herbicide deposits. This study has shown that it is possible to measure quantities of clopyralid deposited on non-absorbent surfaces and rushes with a high degree of accuracy. Unlike other techniques, use of the spectrophotometer provides a more direct measure of herbicide deposition on plants. Although the technique was only used with clopyralid for the purpose of this study, it should be possible to use it with any other herbicide. The large variability in the herbicide deposits results was due to variable output from the wipers rather than the technique itself.

The technique is also likely to work adequately (subject to further studies) with most plant species. The preliminary experiment to measure the recovery rate from rushes showed that this technique was effective for use with plants. However, the plants need to be washed within 10 minutes as the recovery rate decreased with time. It is important that the stock solution used for plants must be from water washed off untreated plants to allow for the effects of chlorophyll and other substances on absorbance readings.

There were differences in output between the three applicators. In Experiment 2, the Eliminator deposited the greatest amount of herbicide on the artificial weeds. In Experiment 3, the Rotowiper deposited the greatest amount of herbicide on the artificial weeds. However, the Weedswiper deposited the least amount of herbicide on the artificial weeds in both experiments. This variability between experiments was attributed to the variable moisture levels of the pads/carpet. This study infers that if the Weedswiper can achieve adequate weed control levels with less herbicide, then the Rotowiper and Eliminator can achieve similar levels of control at below saturation levels thereby minimising risk of pasture damage.

The results clearly show that it is difficult to maintain the moisture level of pad/carpet of the applicators and this makes it difficult to know how much herbicide is being applied. This might explain the variability in the level of weed control achieved in the field (Chapter 5). The inconsistent application of herbicide by weed wipers is an area that needs further research. Other studies have also observed variability in herbicide output with different applicators. Lutman et al. (1982) applied glyphosate to various weed species using two roller applicators and one rope-wick applicator and showed high variability of up to 5-fold difference. The Weedswiper which had the lowest co-efficient of variation (Fig 7.7) in output has an electronic moisture sensor (hydrostat) which makes it possible to make a consistent calibration of the wiper. The Rotowiper uses a subjective assessment of the wetness of the rollers, and this is likely to be the reason why its co-efficient of variation was higher than the other two wipers (Fig 7.6). The Eliminator requires that the operator set the desired level of wetness although the recharge of the carpet does not depend on how much is lost to the weeds but on a pre-determined cycle.

Lutman et al. (1982) showed a relationship between wiper output and damage to the under-storey plants with applicators that had a higher output also causing more damage. The same study also showed that wipers with low output are likely to achieve adequate control with plant species that tend to have a larger surface area of foliage exposed to the wiper (e.g. docks) but poor control with other more erect species. Because of the variability in output of these wipers, it is not possible to come up with a recommendation of how to relate application rates to different wipers.

The herbicide output depends on the wetness of the wiper. Although maximum moisture levels resulted in more herbicide deposited on the ‘weeds’, presumably wetter pads are more likely to cause pasture damage. The nature of the plant being wiped also determines whether pasture damage is likely to occur or not. It has been shown that use of a saturated wiper against rigid plants causes damage due to excess dripping as a result of more resistance to the wiper compared to flexible plants (Schepers & Burnside, 1979).

Herbicide output was only slightly related to speed of the application. This confirms earlier results by other researchers who found no consistent relationship between speed and herbicide output of wipers (Lutman et al., 1982; Schneider et al., 1982; Martin et al., 1990). The most likely reason why speed does not have an influence on output is because the surface area of the weed that is exposed to the wiper does not change with speed within practical limits. Thus, increasing speed will significantly reduce the time required for weed control, allowing farmers to use the saved time for other competing priorities. However, since the experiment was carried out on level ground, it is not known what effect speed might have on bumpy ground whereby herbicides are likely to bounce off the applicator.

Other researchers found a reduced level of control of weeds when the forward speed was increased (Derting, 1981; Wu & Derting, 1981). Yet other studies have found an interaction between speed and design of the wiper on its effectiveness to control bracken fern (*Pteridium aquilinum* var. *esculentum* (L) (Kuhn)) using glyphosate, with the effectiveness of the transverse rope applicator being more dependent on speed while for the longitudinal applicator, speed was not important (Moore & Jones, 1988). The same study showed that at lower speed, transverse applicators tend to push the plants down and away from the wicks resulting in less output, whereas at high speed the plants are hit much harder and tend to coil around the applicator thereby receiving more herbicide. This situation would be unlikely with most weeds. Lutman et al (1982) could not relate performance of the wipers to design since the performance of a rope-wick applicator was intermediate in performance to two roller-type applicators in his comparison of the three wipers.

The lack of relationship between speed and wiper output is an important finding considering that in boom-spraying speed has a huge influence on application rates. Accurate application of herbicides from sprayers requires a known constant speed of travel (Wolf & Edmisten, 1986) with a generally recommended forward speed of less than 10 km/hr (Anderson, 1996; Zimdahl, 1999) as too slow a speed will result in over-application. Conversely, a faster speed may result in under-application. Also, with older model rope-wick applicators a slower speed was likely to be more effective than a faster speed since the herbicide recharge rate of the rope in the passive system (capillary movement) was much slower.

The most important research need is to investigate the most desirable herbicide output for a given weed situation to permit standardisation of herbicide recommendations. This can only be possible if wiper applicators were to be fitted with electronic moisture sensors that will enable the pads to be kept at a desired level of saturation making it possible to know how much each wiper is applying. This will ensure uniformity of output and make it possible to come up with recommendations for herbicide concentrations to be used for each wiper in relation to its output.

7.5 Conclusions

The spectrophotometer is a useful tool in measuring herbicide output from weed wipers. The problems of variability in wiper output can be dealt with in the short-term by increasing herbicide concentration to ensure sufficient herbicide is applied to the weeds at all times. In the long-term, weed wipers could be fitted with electronic moisture sensors to ensure uniformity of application and consistency.

7.6 References

ANDERSON WP (1996) Weed Science : Principles and Applications. West Publishing Company., USA.

DALE JE (1978) The rope-wick applicator - a new method of applying glyphosate. In: *Proceedings of the 31st Annual Meeting of the Southern Weed Science Society*., 332.

DERTING CW (1981) Correlation of rope wick design and components with glyphosate performance. In: *Proceedings 1981 Annual Meeting Southern Weed Science Society*, Dallas, 305-310.

FURRER JD, LUESCHEN WE, MARTIN AR & BURNSIDE OC (1980) Comparative effectiveness of new generation application for controlling weed escapes in soybeans and grain sorghum. In: *Proceedings 1980 North Central Weed Control Conference*, 59-60.

GREKUL CW, COLE DE & BORK EW (2005) Canada thistle (*Cirsium arvense*) and pasture forage responses to wiping with various herbicides. *Weed Technology* **19**, 298-306.

LUTMAN PJW, OSWALD AK & BYAST TH (1982) The chemical estimation and biological activity of glyphosate deposited on four plant species by one rope wick and two roller applicators. In: *Proceedings 1982 British Crop Protection Conference: Weeds,* 1001-1008.

LYKOS P (1992) The Beer-Lambert law revisited - A development without Calculus. *Journal of Chemical Education* **69**, 730-732.

MAKEPEACE W & THOMPSON A (1982) Ragwort control using a rope wick applicator. In: *Proceedings 1982 New Zealand Weed and Pest Control Conference*, Palmerston North, New Zealand, 256-260.

MARTIN P, FULLERTON DK & JAMES TK (1990) Weed trials using a rotary weed wiper. In: *Proceedings 1990 New Zealand Weed and Pest Control Conference*, Dunedin, New Zealand, 262-265.

MAYEUX HS, JR. (1987) Application of herbicide on rangelands with a carpeted roller: shrub density influences volume, dosage, and rate. *Weed Science* **35**, 444-448.

MAYEUX HS, JR. & CRANE RA (1985) Application of herbicides on rangelands with a carpeted roller: evaluation of four herbicides for control of honey mesquite. *Journal of Range Management* **38**, 233-237.

MCWHORTER CG & DERTING CW (1985) Methods of application of glyphosate. Butterworths, London UK.

MEEKLAH FA & MITCHELL RB (1984) Evaluation of herbicides for control of Californian thistle. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 20-23.

MOORE JH & JONES SM (1988) Bracken control with rope-wick applied glyphosate. *Plant Protection Quarterly* **3**, 65-68.

O'CONNOR B (2004) Novachem Manual 2004/2005. In: *Novachem Manual* (Novachem Services Limited), Palmerston North 488 pp.

RICCI RW, DITZLER M & NESTOR LP (1994) Discovering the Beer-Lambert Law. *Journal of Chemical Education* **71**, 983-985.

RICHARDSON RG (1984) Fluorescent tracer techniques for measuring total herbicide deposits on plants. *Australian Weeds* **3**, 123-124.

ROTOWORKS (2007) Rotowiper. [Online]: Available: http://www.rotowiper.co.nz/Using.htm [Retrieved 21 August 2007].

SAS INSTITUTE (2004) Statistical Analysis system. SAS version 9.1.

SCHEPERS JS & BURNSIDE OC (1979) Electronic moisture sensor for maintaining herbicide solution on a roller applicator. *Weed Science* **27**, 559-561.

SCHNEIDER GL, KOEHLER CB, SCHEPERS JS & BURNSIDE OC (1982) Roller applicator for shattercane (*Sorghum bicolor*) control in row crops. *Weed Science* **30**, 301-306.

SHARP RB (1974) Spray deposit measurement by fluorescence. *Pesticide Science* **5**, 197-209.

SHARP RB (1976) Measurement of herbicide spray deposits on foliage by fluorescence. 1. Paraquat deposits on *Vicia faba*. *Pesticide Science* **7**, 315-319.

THOMPSON JE (2006) A simple method for rapidly obtaining absorption spectra with a spectronic-20D+ spectrophotometer. *Journal of Chemical Education* **83**, 913-914.

WOLF DD & EDMISTEN KL (1986) Uniform travel speed for manually propelled sprayers and spreaders. *Agronomy Journal* **78**, 211-212.

WU CH & DERTING CW (1981) Operational variables and glyphosate performance through rope wick applicators. In: *Proceedings 1981 Annual Meeting Southern Weed Science Society*, Dallas, 301-304.

ZIMDAHL RL (1999) Fundamentals of weed science. Academic Press, San Diego.

Chapter 8

8 General Discussion and Conclusions

8.1 Introduction

Phenoxy herbicides play an important role in weed control in New Zealand pastures (Holland & Rahman, 1999). Widespread use of these herbicides has led to a multitude of problems as discussed in Chapter 1. Alternative application techniques to boom spraying such as wiper application of herbicides and spot spraying are ways by which the quantity of herbicides used in pastures can be reduced. These targeted options allow the use of more effective, less selective herbicides such as clopyralid, glyphosate, metsulfuron, picloram and triclopyr.

The use of herbicides with different modes of action and different target sites reduces the chances of weeds developing resistance. Targeted herbicide application also greatly reduces the amount of herbicides used, leading to both economic and environmental benefits (Combellack, 1989; Miller, 2003). Weed wiping and spot spraying are also likely to have a more favourable public image than boom spraying.

It is important though to realise that spot spraying and weed wiping on their own will not solve all the weed problems in pasture. If weeds are widespread then spot spraying is often not practical. For plants like ragwort and nodding thistle, weed wipers can not be used until flowering due to lack of a height differential between the rosettes of these weeds and pasture. By the time stem elongation occurs, pasture utilisation has been reduced for many months. It is also possible that herbicides such as clopyralid and metsulfuron will kill developing seeds if wiping is carried out when the plants are in the early stages of flowering.

The aim of this thesis was to investigate strategies to use herbicides more efficiently in pastures. To meet the aims of the thesis, factors that determine the optimum performance of weed wipers were investigated as well as ways in which the spot spraying technique could be improved. The use of wipers was assessed first by investigating effectiveness of translocating herbicides in controlling Californian thistles (*Cirsium arvense* (L.) Scop.). The second study with weed wipers investigated pasture damage resulting from wiper application of herbicides. Another study was conducted to develop a technique to measure herbicide output from different wipers in order to come up with standard recommendations for rates to be used in each wiper. The results of these experiments are discussed in Chapters 5 to 7.

Other experiments were conducted to study spot-spraying of herbicides to determine how to minimise damage to plants growing in the vicinity of the target weeds, as described in detail in Chapters 3 and 4. This chapter discusses the major findings of this research and prospects for future research arising from this work.

8.2 Wiper application of herbicides to weeds

Californian thistle can be a problematic weed due to its extensive root system and huge carbohydrate reserves that make it difficult to control. This can partly explain the poor results in some of the field trials. A total of five experiments was carried out in the field to control Californian thistles, and pasture damage only occurred once but the level of weed control was also high on this occasion. Subsequent trials produced poor control but less pasture damage. However, successful control and minimal damage can be achieved with a combination of proper timing and choice of herbicide.

8.2.1 Weed control

Californian thistle was treated with a Rotowiper applicator on five different occasions over the trial period. In the first trial, there was over 90 % reduction (glyphosate and clopyralid) in the thistle stems when assessed in the following spring (Chapter 5, Fig 2). To achieve above 90% control using a Rotowiper shows that these applicators have good potential for controlling the weed. However, to achieve this level of control, the thistles need to be at the appropriate growth stage and are in a condition that allows translocation of herbicides to the root system in sufficient quantities to achieve adequate control. Glyphosate, clopyralid and metsulfuron all gave good control, but triclopyr/picloram was less effective, especially from a single pass of the wiper. Other selective approaches such as use of post-emergence phenoxy sprays at the rates required to control established weed infestations in pastures are not as effective against mature weeds and can cause significant short-term damage to clovers (Hartley, 1983; Popay et al., 1984).

Although a double pass was more effective than a single pass for glyphosate and triclopyr/picloram, the reduction in Californian thistle stems achieved by clopyralid, glyphosate and metsulfuron with a single pass was still above 75% for all herbicides (except triclopyr/picloram), which is better than other wiping treatments in a double pass or use of selective herbicides such as MCPB (Meeklah & Mitchell, 1984). This shows that the wiper was depositing herbicides in sufficient quantities to kill the thistles even with a single pass.

However, field experiments in the following seasons (2006 and 2007) were not as successful as the first experiment (Chapter 5, Fig 6). There is a number of possibilities as to why control was not as successful. Variable growth of Californian thistle associated with differences in seasons mean that control of this weed with herbicides is inconsistent (Armor & Harris, 1977). The different stages at which the Californian thistle was treated could have played a part in the poor control together with the plants being tolerant of the herbicides due to stress from drought and insect attack. The thistles in the second experiment were covered in sooty mould as a result of aphid infestation. The stress caused by aphid infestation coupled with drought conditions at the time could have reduced the effectiveness of the herbicides. In the first experiment, the plants were larger and more uniform with an average height of 1.1 m. With the height of the wiper set at 18 cm, the proportion of the weed wiped (84%) was high. In contrast, the weeds at the second site for the second and third experiments were much smaller and variable in height and the proportion of the weed wiped was as low as 54%. In addition, up to 9% of the Californian thistles were below the wiping height in the second and third experiments and thus did not receive any herbicide. In the first experiment, only 5% of thistles were below the wiping height. The amount of herbicide applied is directly proportional to the length of the weed contacted by the wiper (Haydon, 1983). It is important that a large proportion of individuals within a clone are wiped since not all shoots remain interconnected through the root system (Donald, 1992).

The physiological effect on herbicide effectiveness after flower heads (26%) of the Californian thistles were eaten by sheep in the second experiment is not known. It is likely that the some of the photo-assimilates could have been used for development of new shoots while any excess sugars would have been stored in the roots. This re-distribution of photo-assimilates within the plants could have affected the effectiveness of the herbicides.

It is also possible that the technicians operating the wiping equipment applied different amounts of herbicide in each of the five experiments due to the subjective method of judging the wetness of the wiper. A possible explanation for these results is that in the first field trial, the wiper was operated at a higher moisture level than subsequent applications. There is a need to improve the design of the wiper applicators so that output of herbicide is not subjective, thus allowing consistent rates of application. Different trials with artificial weeds have shown the output of these wipers can be variable, even when operated by the same person (Figs 7.5-7.8). The recommendation by the distributors of the Rotowiper to add a foaming agent to the herbicide so as to estimate the wetness of the wiper appears to be too subjective to give consistent results.

8.2.2 Choice of herbicide

The choice of herbicide to control weeds depends on several factors including the type of weeds present and cost. Glyphosate, clopyralid and metsulfuron are all known to be highly effective against Californian thistle (Pollak & Bailey, 2001). Although the effectiveness of herbicides in controlling weeds is paramount, other factors such as damage to pasture and the cost of the herbicide are also important. For example, clopyralid is known to be very effective for Californian thistle control (Samunder & Malik, 1992) but relatively more expensive compared to glyphosate and metsulfuron (Table 8.1).

Table 8.1 Relative cost of herbicides (wiping) used in the trials.

Product	**Active ingredient**	**Product Price**	**Price/unit**	**Recommended rate /40L**	**Product cost/40 L**
Answer	200g/kg metsulfuron	$1030/4.5kg	$0.23/g	120g	$27.47
Glyphosate 360	360g/L glyphosate	$1226/200L	$6.13/L	2 L	$12.26
Versatil	300g/L clopyralid	$1436/20L	$71.80/L	1 L	$71.80
Tordon Brushkiller	100g picloram&300g triclopyr/L	$387/5L	$77.40	1L	$77.40

Source: Burtt, 2006.

To fill up a 40 litre tank at the recommended rates costs $12.30 for glyphosate and $77.40 for triclopyr/picloram for the cheapest and most expensive herbicides, respectively (Burtt, 2006). The cost for metsulfuron and clopyralid is $27.50 and $71.80, respectively. Glyphosate would definitely be the herbicide of choice considering its effectiveness, low cost, lack of damage to clover and other environmental benefits such as lack of residual activity in the soil. Triclopyr/picloram costs over six times more than glyphosate and is less effective than glyphosate for thistle control. Metsulfuron is also relatively inexpensive compared to clopyralid and triclopyr/picloram and extremely low use rates of 0.6 g a.i /L of water makes it a viable alternative to glyphosate.

The type of weed to be controlled also influences the choice of herbicide. For example, rushes are generally not controlled by clopyralid, triclopyr/picloram but are susceptible to glyphosate. In this instance, the effectiveness of the herbicide rather than other considerations becomes the main deciding factor.

The effect of herbicides on pastures also plays an important part in herbicide selection. Some herbicides are more damaging than others with metsulfuron being the most damaging since it is capable of both killing clover and severely suppressing perennial ryegrass. Clopyralid and triclopyr/picloram at recommended rates only remove clover leaving the grass intact, and so clopyralid is often recommended to farmers for wiping thistles when grass seed-heads are present. Wiping with glyphosate has little effect on clover and only causes temporary damage to grass (Fig 5.2). However, if the weed density is low and the area likely to be damaged is small, farmers may tolerate the damage caused and use the cheaper metsulfuron than opt for more expensive herbicides such as clopyralid or triclopyr/picloram.

8.2.3 Application rates

The discussion points in this section have arisen as a result of the difficulty encountered in comparing similar wiping trials. There has been no consistency in the reporting of herbicide rates used with wiper applicators. Some researchers refer to a 1:3 dilution of glyphosate as meaning one part product to two parts water (Grekul et al., 2005) while others consider the 1:3 dilution rate to mean one part product to three parts water (Martin et al., 1990). The difference in dilution rates cited above for the two authors gives an 8% difference in concentration of the herbicide making comparison of trials difficult. It is therefore recommended that concentration rates for research work be standardised by expressing them as quantity of active ingredient per litre of water.

Past researchers have mainly used extremely high rates of 180 g a.i glyphosate/ litre of water (Derting, 1987), although there has been a shift to lower rates, mostly 19 g a.i per litre of water. A study by Martin et al. (1990) using glyphosate 19 g, 38 g and 180 g a.i per litre of water, respectively, achieved no difference in ragwort control (*Senecio jacobaea* L.). In contrast, Boerboom & Wyse (1988) found low rates (1:40) gave better control of

Californian thistles than 1:10 and 1:3 dilution rates. Another study by Mayeux & Crane (1984) using glyphosate to control goldenweeds (*Isocoma* spp.) and false broomweed (*Ericameria austrotexana (*M. C.) Johnston.) found no differences in control of the weeds even with a 5-fold difference in herbicide concentration. Optimum concentration rates for different chemicals and weed species need further investigation. However, these dilution rates also need to be related to the output of the wipers if useful recommendations for herbicide concentrations to be used with each wiper are to be achieved.

8.2.4 Choice of weed wiper

The choice of a wiper that a farmer can use depends on various factors including ease of operation and the price of the machine. Current wipers have evolved over a long time from the days of the Stoneville and rope wick applicators. In the older model wick applicators, speed had a significant bearing on efficiency since the wick was required to be in contact with the weed long enough to deposit sufficient quantities of herbicide (Turner, 1981). Results from this study have shown that speed is not an important factor in herbicide output. The older models had much lower output and it was necessary to have a double pass and a highly concentrated herbicide solution in order to achieve good control.

A shift from passive to pressurised systems with much larger wiping surfaces has meant that the wiper output has improved such that a double pass may not be necessary in some situations and less concentrated solutions are currently being used. However there is more room for improvement including making the output of the wipers more consistent if good control of weeds is to be repeatable. The limitations in each wiper can be overcome with continuing feedback from both farmers and researchers alike.

The Eliminator and Rotowiper had on average twice the output of the Weedswiper although their output was extremely variable. In a situation where the weed density is high and to guarantee that enough herbicide is being deposited on to weeds, wipers with higher output may be preferable.

However, if the Weedswiper is used, the concentration of the herbicide could be doubled to allow for the lower output.

The Weedswiper has an electronically controlled hydrostat system that maintains the moisture of the wiper pads at a constant level to maintain consistency of output. This consistency was confirmed by our results that showed the Weedswiper to have the lowest coefficient of variation in output compared to the other wipers (Fig 7.6). The Eliminator has an electronic pump controller which the operator sets to the desired level. The level at which the switch is set determines the frequency at which the pump automatically turns on and off. The operator has to relate weed density to the level set. The Rotowiper, on the other hand, requires the operator to continuously turn on the pump by judging the wetness of the wiper. This requires an operator to replenish the herbicide used up by turning on the switch to increase the amount of herbicide before approaching a heavy patch of weeds and turning the switch off when the density is lower.

The Rotowiper and Weedswiper come in different models with working widths ranging from 1.8 m to 6.0 m and 2.3 m to 4.7 m for the Rotowiper and Weedswiper, respectively. The Eliminator comes in one model with a working width of 2.3 m. However, the working width of the Eliminator can be doubled or tripled by coupling two or three wipers together (C-Dax, 2007). This will require having to buy extra wipers, which, judging by the relatively low cost of the Eliminator, is feasible. The choice of a wiper will thus also be influenced by the width of the wiper in relation to the area to be treated with wider wipers suitable for agricultural contractors. However, because of unevenness in the terrain in hilly areas, wide booms may not be suitable for use while shorter units such as the eliminator could be better suited to such areas.

There is a big range in prices between the three wipers and different models of the same wiper. (The prices quoted below are current as provided by the manufacturers or their distributors in November 2007). The Rotowiper with the shortest working width (1.8 m) costs $3870 while the 4.5 m costs $6045 for tow-behind units with some tractor-mounted models (working width 6.0m) having a price of more than $10 000. The current prices for the Weedswiper are $3285 and $3900 for a 2.3 m and for 4.7 m working width, respectively while the price for the Eliminator (working width 2.3 m) is $1885.

8.2.5 Moisture Sensors

The herbicide output of weed wipers is primarily influenced by the moistness of the wiping pad (Fig 7.4). However, there is no objective means of ensuring that a desired moisture level is maintained for both the Eliminator and Rotowiper. Electronic moisture sensors like the one on the Weedswiper are one way by which consistency in output could be maintained. Once an optimum moisture level is determined, it can be maintained by use of electronic moisture sensors at a level that does not cause damage to pasture (Schepers & Burnside, 1979). This ensures less variability in herbicide output. The Weedswiper does not depend on the expertise of the operator to maintain consistency in output.

Electronic moisture sensors on rotary weed wipers have been investigated in New Zealand (Toor & Brewster, 1995). However, currently there is only one commercial wiper that utilises this important improvement in design. The above-cited authors identified reservations that farmers might have, which include potential malfunction and cost of repairs.

8.3 Causes of pasture damage from wiper application of herbicides

8.3.1 Introduction

Despite widespread use of weed wipers, apparently no study had looked in detail at reasons why damage is sometimes caused to pasture. The use of wiper applicators does not always result in extensive damage as was the case in the first experiment. Subsequent field trials during this study did not result in any widespread damage. One of the objectives of this thesis was to investigate how pasture plants become exposed to herbicides when weeds are wiped. Possible causes of pasture damage were assessed in a series of experiments investigating factors that were considered likely to be responsible. Results from the study to investigate pasture damage (Chapter 6) showed that although there are several ways by which herbicides can be unintentionally transferred to pasture, quantities are not always sufficient to cause any damage. Herbicides flowing down the stems of weeds are likely to cause only localised damage and this can be worsened if the carpet/wick is overly wet. There was evidence that metsulfuron affected clover plants in the exudation trial. Although the damage to the clover in the exudation trial was only minor, there is a need to investigate this further. Application of herbicides to grass seed-heads also had no significant effect on damage although symptoms of herbicide effect on daughter tillers could be seen.

8.3.2 Rainfall

Rainfall appeared to be the single most important factor causing pasture damage following wiper application of herbicides (Section 5.4). Simulated rainfall one day after herbicide treatment caused more damage to white clover and perennial ryegrass than simulated rainfall after five days of herbicide treatment (Chapter 6, Fig 8). This suggests that the sooner the onset of rainfall after treatment, the higher the risk of damage. In the field experiments, there was damage from 8 mm of rain 3 days after application, but none from 12 mm of rain after 9 days as well as no damage from light rain within a day after glyphosate treatment.

As with any other method of applying herbicides, weather forecasts must be taken into account when using wiper applicators. Also, weed wipers could be used more at times of the year when rainfall is less likely such as in summer. Summer time coincides with the post-flowering stage of most Californian thistles and this might improve the effectiveness of the herbicides. It is also the only time of year when species such as ragwort and nodding thistle are taller than the pasture anyway.

8.3.3 Herbicides and herbicide formulation

In the one field experiment in which we experienced pasture damage after wiper application of herbicides, metsulfuron was the most damaging chemical we assessed, causing death and suppression of both clover and ryegrass.

Clopyralid and triclopyr/picloram were also very damaging to clover but had no visible effect on perennial ryegrass. Glyphosate was the least damaging herbicide with negligible effect on clover and only a minor effect on perennial ryegrass.

Herbicide formulation probably also plays a role in pasture damage. Ester formulations are generally known to penetrate plants faster and are more resistant to being washed off by rain than salt formulations (Bovey & Diaz-Colon, 1969; Bovey et al., 1990). An indirect field and glasshouse comparison of the damage caused by the salt formulation of triclopyr/picloram (Tordon Gold) and triclopyr/picloram (Tordon Brushkiller) in which the triclopyr is formulated as an ester relative to clopyralid and metsulfuron showed Tordon Gold to be more damaging than Tordon Brushkiller. If triclopyr/picloram is to be applied by wipers, then the ester formulation should be used instead of the amine salt formulation.

8.3.4 Further research

The relationship between the quantity of herbicide applied, effectiveness of control, amount of rainfall and resulting pasture damage needs further study.

The use of detergents in wipers (as recommended by the manufacturers of the Rotowiper) also needs to be investigated. Does it make the herbicide more susceptible to being washed off in the event of rain? The addition of detergents means that the level of surfactants in the herbicide solution becomes higher than is generally recommended for the herbicide. Surfactants are usually used at a concentration between 0.1 and 0.5% and generally increases herbicide uptake with increasing surfactant concentration from 0.01 to 1% (Wang & Liu, 2007). In some cases higher surfactant concentrations may have an antagonistic effect on pesticide uptake as can be the case with glyphosate uptake in grasses using organosilicone surfactant Silwet L-77 (Gaskin & Stevens, 1993; Liu, 2003). There is a need to investigate further how this increased concentration impacts on herbicide effectiveness.

8.4 Development of a technique to measure output of herbicides from wiper applicators

8.4.1 Introduction

Weed wipers currently available on the market differ in design and herbicide output. Despite this difference, the recommended herbicide dilution rates for the wipers is the same (O'Connor, 2004). There has been no reliable technique developed to accurately measure output from these wipers. Therefore, one of the objectives of this thesis was to develop a technique to accurately measure how much herbicide is applied to weeds by weed wipers to assist with future research.

8.4.2 The potential of the spectrophotometric technique

One of the major outcomes of this study was the development of the spectrophotometric technique to measure output by wipers. This study has shown that it is possible to measure small quantities of clopyralid deposited on non-absorbent surfaces with a high degree of accuracy. As little as 0.02 g ai clopyralid could be accurately measured in a litre of water, a dilution rate of 1:15 000 (herbicide : water). The herbicide recovery rate from rushes (*Juncus* spp.) was also high, provided the plants were washed within ten minutes of application.

The technique is simple and easy to use requiring only washing herbicides off the targets and analysing the sample in the spectrophotometer. Unlike other techniques that have been used before, there is no need to mix the sample with other chemicals to estimate the amount of herbicides. The technique has potential to be developed further, and trials could investigate whether other herbicides could be quantified as accurately. There is also a need to investigate the use of the technique with other weed species. However, because a spectrophotometer is required, the technique is not suitable for use by farmers or agricultural contractors for calibrating wiper output.

The technique could also be used to estimate herbicide absorption rates. Known amounts of herbicides could be applied to plants, and by washing the herbicides off at different time intervals, the absorption rates could be determined. Also, plants of different sizes and morphology could be wiped with herbicides and then the amount wiped related to the size of the plants.

8.4.3 Variability in herbicide output from weed wipers

The use of the technique made it easy to measure relative herbicide output from the Eliminator, Rotowiper and Weedswiper. The Weedswiper deposited the least amount of herbicide. There was a large amount of variation in the amount of herbicides deposited to individual “weeds”, despite the “weeds” being uniform. This variability in output from the wipers needs to be reduced to give results that are more reliable. However, for all the three wipers, speed of application makes very little difference to the amount applied. The Weedswiper was the least variable, probably because of the automated moisture sensor in the wiper. The Eliminator and Rotowiper outputs were extremely variable. This amount of variation appears to make the application technique unreliable. Because of this large variation, recommendations for herbicide concentrations to be used in wipers should allow for this variation in output, to ensure that at least the minimum lethal herbicide dose is applied to every weed. This will still not result in significant amounts of herbicide being applied per hectare considering that herbicide is only being wiped on to the weeds, which is often only 5% of the pasture compared to applying it over the whole area by boom-spraying. The amount of herbicide solution used is estimated at as little as 4 L/ha for the Eliminator depending on weed density (C-Dax, 2007) and probably much less for the Weedswiper.

The results showed that the Weedswiper consistently deposited less herbicide on to artificial weeds than the other two wipers. It can therefore be inferred that if the Weedswiper has been successfully used to control weeds in pastures, the Eliminator and Rotowiper can also achieve a similar level of control with lower concentrations of herbicides or lower moisture at the same herbicide concentration. Because of the Weedswiper’s lower output, some of its distributors are now recommending a 4-fold concentration increase to what is normally recommended to get a good kill from wipers (P. Thomson, 26 November 2007, personal communication).

8.4.4 Future research

Future research with wipers not fitted with electronic moisture sensors should attempt to estimate the amount of herbicide being applied so that reasonable comparisons between treatments can be obtained. Electronic moisture sensors will provide an objective means of ensuring consistency in herbicide output for each wiper. In the absence of electronic moisture sensors, field trials with wipers can be done by using upright structures covered in plastic sleeves that can then be analysed in the spectrophotometer as previously shown in Chapter 7. A “weed” structure similar to the one used in this study could also be used by placing it in plots to estimate the wetness of the wiper. Any differences in effectiveness in weed control and pasture damage can then be related to the wetness of the wiper among other factors. This would have made it easier to explain the variable results achieved in the control of Californian thistles (Chapters 5) using the Rotowiper.

8.5 Impact of spot-spraying treatments on pasture plants growing in the vicinity of the target weed

8.5.1 Introduction

The other main aim of this thesis was to study ways of reducing the quantity of non-target herbicide damage during spot spraying. To achieve this aim, experiments were conducted to quantify the extent of the non-target damage and develop strategies to minimise this. Because of the normally patchy distribution of weeds in pastures, it would appear that the overall damage to pastures is small. In situations where the patches are large and weed density within them high, pasture damage from spot spraying can be significant and long lasting. The rates used in the study compared the standard recommendation against a 3-fold over-application to assess the damage that occurs if farmers apply more herbicide than is required especially when plants are sprayed to run-off.

8.5.2 Herbicide effect

Glyphosate and metsulfuron were damaging to both clover and perennial ryegrass and created bare patches. Bare patches from metsulfuron-treated plants were later re-colonised mostly by browntop (*Agrostis capillaris* L.) with little or no clover or weeds while glyphosate-damaged patches were re-invaded by weeds. Re-invasion of bare patches by weeds will defeat the whole purpose of spot-spraying plants as this may result in more weeds than were initially present.

The higher rate of glyphosate was more damaging to clover than the lower rate. Some clover sprayed with the standard rate survived and this meant a quicker patch recovery and less risk of re-invasion by other weeds. Both the standard and high rates of glyphosate were equally damaging to grass. On the other hand both rates of metsulfuron were equally damaging to clover while the higher rate was more damaging to grass. It is therefore possible to minimise the damage caused by metsulfuron and glyphosate by avoiding both over-application and minimising the area sprayed by the herbicide as larger patches took longer to recover (see Section 8.5.3).

Clopyralid and triclopyr/picloram completely removed clover from most plots for the nine months they were monitored. However, these herbicides do not expose bare soil because they have little effect on grass and thus minimises establishment opportunities of new weeds.

The bioassay study gave a useful indicator to how long some herbicides remain active in the soil. Again, the high rates, apart from being more expensive to apply, can be more detrimental in the long term due to prolonged reduction in pasture productivity as a result of residual activity. Because of their long residual activity in the soil, clover is unlikely to be present in the treated patches for more than 9 months in the case of triclopyr/picloram. For all the herbicides, except glyphosate, there was no side invasion of clover stolons into the treated patch suggesting movement of the herbicide outside the treated area possibly killing any germinating seedlings in the vicinity. The activity of the herbicide in the soil would likely have killed any germinating seedlings in the treated patch and its environs further depleting the seed bank of clover. It is likely that unless there is intervention, the patch will take many months to return to its normal composition. Even for herbicides with no residual activity in the soil (e.g. glyphosate), the establishment of weeds in bare patches makes it difficult for clover to re-establish.

8.5.3 Size of patch

The bigger bare patches created from glyphosate treatments were soon colonised by weed species such as black nightshade (*Solanum nigrum* L.), and Scotch thistle (*Cirsium vulgare* (Savi) Ten.). However, the smaller patches from glyphosate treatments were soon covered by clover growing in from the edge of the patch through stolons. This suggests that lateral spread of clover is faster than clover emerging from seed in the recovery of the patches. Although pastures are known to have a huge reserve of white clover seed in the seed bank (Tracy & Sanderson, 2000), the faster establishment of many weed species will make them dominant colonisers of bare ground. Also, white clover hard-seediness can limit germination of seeds in the seed bank.

The larger the patch and the higher the herbicide rate, the longer the pasture takes to recover to its original composition (Chapter 3, Figs 2 & 3). Unfortunately, the recovery time taken by the damaged patches could not be determined since the trial was monitored only for 9 months. The trial was stopped after 9 months due to loss of clover in the patches including untreated ones as a result of the invasion of clover root weevil into the area.

Although lateral spread was an important means by which bare patches of glyphosate could recover, this was not evident with metsulfuron suggesting movement of the herbicide occurred from the experimental patch into the surrounding vicinity. A possible reason for this movement out of the patch could be rainwater dissolving the herbicide and causing lateral spread outside the treated area.

8.5.4 Herbicide recommendations

The choice of herbicide for spot spraying depends on several factors including the effectiveness of the herbicide against target weeds, cost, potential damage to pasture and residual activity. Despite metsulfuron being damaging to pasture, it is probably the most commonly used herbicide for spot-spraying weeds in pastures together with triclopyr/picloram. Spot spraying prices per 100 L of spray solution are: shown in table 8.2

Table 8.2 Relative cost of herbicides used for spot-spraying

Product	**Active ingredient**	**Product Price**	**Price/unit**	**Recommended rate /100L**	**Product cost/100 L**
Answer	200g/kg metsulfuron	$1030/4.5kg	$0.23/g	30g	$6.80
Glyphosate 360	360g/L glyphosate	$1226/200L	$6.13/L	1 L	$6.13
Versatil	300g/L clopyralid	$1436/20L	$71.80/L	0.2 L	$14.36
Tordon Brushkiller	100g picloram&300g triclopyr/L	$387/5L	$77.40/L	0.15L	$11.60

Source: Burtt, 2006.

Metsulfuron is relatively inexpensive and some farmers are able to tolerate the damage it causes to pasture. On the other hand, triclopyr/picloram is not as damaging to pasture but is more expensive than metsulfuron. Although clopyralid and triclopyr/picloram have a more or less similar effect on pasture, the former is more costly, reducing its potential for use in spot spraying. Glyphosate was the most damaging herbicide and generally should not be used for spot-spraying weeds in pastures unless the non-target application is restricted to the barest minimum.

Triclopyr/picloram is a viable alternative. Besides its removal of clover, triclopyr/picloram has no effect on grass at recommended rates. Metsulfuron also has a low residual activity compared to triclopyr/picloram. Although clopyralid has lower residual activity than triclopyr/picloram, presumably the higher cost results in it not being widely used.

8.6 Application of herbicides to the centre of target weeds

Current spot spraying practices using knapsack sprayers and spray guns are not very precise and need to be improved. During spot-spraying, a reduction in the size of damaged area can be achieved by targeting the minimum lethal herbicide dose to the centre of the weed instead of the most commonly practised full coverage.

Also, current recommendations to greatly increase the concentration of herbicides when treating only the centres of rosettes compared to application to run-off are not supported by evidence detailed in this study. However, if herbicide volume is reduced when applying only to the centre, the concentration needs to be adjusted accordingly in order to deliver the required dose. Application to the centres ensures that most of the herbicide not absorbed by the foliage is likely to be absorbed by the roots for herbicides that are active in the soil. In contrast, treating to runoff means any herbicide dripping from the tips of foliage will probably be wasted for weeds with tap roots and also more likely to be intercepted by neighbouring plants.

Applying herbicide to only 5% of the weed rosette means that there is considerable potential for spot-spraying weeds with glyphosate, although further work in the field would be required. Glyphosate does not have residues that will linger to cause problems, and is the cheapest of the herbicides available. At the standard application rate, glyphosate only causes minor damage to clover, so any damage caused would only be to a very small fraction of the field and thus could be acceptable given the benefits.

The commonly practiced technique of spraying plants to run-off means that the area that is damaged by herbicide is likely to be larger than if not sprayed to run-off, especially if the spraying is done when plants are fully grown. This means it becomes inevitable that higher rates will be used, leading to more pasture damage. This effect is likely to be magnified in the field where plants are treated late, and thus are larger, causing more damage to pasture. Treating plants when they are younger should also minimise the herbicide target area and so reduce potential pasture damage. Although the experiment used ragwort and Scotch thistle, the result is likely to be the same with most other weed species in pasture.

Although application of herbicides only to the centre of weeds has now been shown to be a more efficient application method than full plant coverage, there is a need to use appropriate equipment to achieve this precision under field conditions. A local spray equipment company (C-Dax) has recently developed a spray gun fitted with an extended lance which makes it easier for an operator to spray only the centre of weed rosette weeds while seated on an All Terrain Vehicle. Appropriate nozzle selection may also help reduce the area covered.

8.7 Conclusions

The research presented in this thesis resulted in the following conclusions:

- Wiper applicators with properly adjusted herbicide concentration rates and wiper pad wetness have great potential for controlling weeds that grow higher than the pasture. They can be used with highly potent herbicides such as glyphosate, metsulfuron, picloram and triclopyr for control of problem weeds such as Californian thistles. Treating weeds only where they occur reduces the amount of herbicide used, reducing contamination of the environment and minimising pasture damage.
- Because of the variability in output of some wipers, the concentration rates to be used in each wiper need to be high enough to compensate for occasional low quantities being wiped on weeds.
- Pasture damage can sometimes occur following wiper application of herbicides, and rain falling soon after wiper application appears to be the major cause of this damage.

- Spectrophotometers are a useful research tool to measure output of clopyralid from wiper applicators. This improves our ability to study factors affecting weed control and pasture damage from wiper-application of herbicides, such as the minimum dose to kill weeds. The technique was used to show speed of application has little effect on deposition of herbicides to weeds from wipers. The technique also has potential for use in herbicide absorption studies.
- Weeds colonising from seeds are more likely to appear in large rather than small gaps after damage from herbicides. Lateral spread of clover stolons is faster than clover seedling emergence in the recovery of small gaps in pastures. The activity of the herbicide in the soil would likely have killed any germinating seedlings further depleting the seed bank of clover. It is likely that unless there is intervention, the patch will take many months to return to its normal composition.
- Herbicide damage to pasture from spot-spraying weeds can be decreased by spraying only the centre of the weed and does not require extra herbicide to achieve control.

8.8 References

ARMOR RL & HARRIS RV (1974) Distribution and seed production of *Cirsium arvense* (L.) Scop). in Victoria, Australia. Weed Research **14**, 317-323.

BOERBOOM CM & WYSE DL (1988) Influence of glyphosate concentration on glyphosate absorption and translocation in Canada thistle (*Cirsium arvense*). *Weed Science* **36**, 291-295.

BOVEY RW & DIAZ-COLON JD (1969) Effect of simulated rainfall on herbicide performance. *Weed Science* **17**, 154-157.

BOVEY RW, MEYER RE & WHISENANT SG (1990) Effective simulated rainfall on herbicide performance in huisache (*Acacia farnesiana*) and honey mesquite (*Prosopis glandulosa*). *Weed Technology* **4**, 26-30.

BURTT ES (2006) Financial Budget Manual, Farm Management Group, Lincoln University.

C-DAX (2007) Weed wiper - product range. [Online]: Available: http://www.cdax.co.nz/efx/include/common/category.asp?country=AU&CatID=21 [Retrieved 21 November 2007].

COMBELLACK JH (1989) Resource allocations for future weed control activities. In: *Proceedings 1989 New Zealand Weed and Pest Control Conference*, New Plymouth, New Zealand, 15-30.

DERTING CW (1987) Wiper application. In: *Methods of applying herbicides* Vol. 4 (eds CG McWhorter & MR Gebhardt.), 207-229. Weed Science Society of America, USA.

DONALD WW (1992) Herbicidal control of *Cirsium arvense* (L.) Scop. roots and shoots in no-till spring wheat (*Triticum aestivum* L.) *Weed Research*, **32 (4),** 259-266.

FRANK JR & TWORKOSKI TJ (1994) Response of Canada thistle (*Cirsium arvense*) and leafy spurge (*Euphorbia esula*) clones to chlorsulfuron, clopyralid, and glyphosate. *Weed Technology* **8**, 565-571.

GASKIN RE & STEVENS PJG (1993) Antagonism of the foliar uptake of glyphosate into grasses by organosilicone surfactants. Part 1: effects of plant species, formulation, concentration and timing of application. *Pesticide Science* **38**, 185-192.

GREKUL CW, COLE DE & BORK EW (2005) Canada thistle (*Cirsium arvense*) and pasture forage responses to wiping with various herbicides. *Weed Technology* **19**, 298-306.

HAGGAR RJ, OSWALD AK & RICHARDSON WG (1986) A review of the impact and control of creeping thistle (*Cirsium arvense* L.) in grassland. *Crop Protection* **5**, 73-76.

HARRINGTON KC & IVENS GW (1983) The influence of growth stage and application site on Californian thistle control by glyphosate. In: *Proceedings 1983 New Zealand Weed and Pest Control Conference*, Hastings, New Zealand, 99-103.

HARTLEY MJ (1983) Effect of Scotch thistles on sheep growth rates. In: *Proceedings 1983 New Zealand Weed and Pest Control Conference*, Hastings, New Zealand, 86-88.

HAYDON A (1983) Wick booms have strengths and weaknesses. *New Zealand Journal of Agriculture* **146**, 8-9.

HOLLAND PT & RAHMAN A (1999) Review of trends in agricultural pesticides use in New Zealand (ed. Ministry of Agriculture and Forestry), 53.

LIU ZQ (2003) Characterisation of glyphosate uptake by grass species. *Australian Journal of Agricultural Research* **54**, 877-884.

MARTIN P, FULLERTON DK & JAMES TK (1990) Weed trials using a rotary weed wiper. In: *Proceedings 1990 New Zealand Weed and Pest Control Conference*, Dunedin, New Zealand, 262-265.

MAYEUX HS, JR. & CRANE RA (1984) Application of Herbicides with a Carpeted Roller: Control of Goldenweeds (*Isocoma* spp.) and False broomweed (*Ericameria austrotexana*). *Weed Science* **32**, 845-849.

MEEKLAH FA & MITCHELL RB (1984) Evaluation of herbicides for control of Californian thistle. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 20-23.

MILLER PCH (2003) Patch spraying: future role of electronics in limiting pesticide use. *Pest Management Science* **59**, 566-574.

O'CONNOR B (2004) Novachem Manual 2004/2005. In: *Novachem Manual* (Novachem Services Limited), Palmerston North 488 pp.

POLLAK R & BAILEY AD (2001) Grasping the thistle - an integrated strategy for control of *Cirsium arvense*. In: *Proceedings 2001 British Crop Protection Conference: Weeds,* Brighton, UK, 231-236.

POPAY AI, EDMONDS DK, LYTTLE LA & PHUNG HT (1984) Timing of MCPA applications for control of giant buttercup. In: *Proceedings 1984 New Zealand Weed and Pest Control Conference*, Christchurch, New Zealand, 17-19.

SAMUNDER S & MALIK RK (1992) Evaluation of clopyralid against *Cirsium arvense*. *Tests of Agrochemicals and Cultivars*, **13**, 46-47.

SCHEPERS JS & BURNSIDE OC (1979) Electronic moisture sensor for maintaining herbicide solution on a roller applicator. *Weed Science* **27**, 559-561.

TOOR RF van & BREWSTER DS (1995) Automatic herbicide dispenser for rotary wipers. *Applied Engineering in Agriculture* **11,** 377-380**.**

TRACY BF & SANDERSON MA (2000) Seedbank diversity in grazing lands of the northeast United States. *Journal of Range Management* **53**, 114-118.

TURNER N (1981) The weed wiper - an overall approach. *British Sugar Beet Review* **49**, 17-20.

WANG CJ & LIU ZQ (2007) Foliar uptake of pesticides--Present status and future challenge. *Pesticide Biochemistry and Physiology* **87**, 1-8.