Herbicides to replace flupropanate for the control of serrated tussock (*Nassella trichotoma* (Nees) Arech.)

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Summary

Experiments carried out in the southern tablelands of New South Wales from 1995 to 1999 to investigate possible herbicide replacements for flupropanate for killing serrated tussock (*Nassella trichotoma* (Nees) Arech.) showed that glyphosate was the only practical alternative available at present. However, results from applying rates within + or - 0.20 kg a.i. ha^{-1} of the following, 0.45, 0.90, 1.35, 1.80, 2.25, 2.70 and 3.15 kg a.i. ha^{-1} to unburnt/ungrazed serrated tussock varied, respectively, from 0 to 81% kill, 0–91%, 0–99%, 75–100%, 78–100%, 80–100% and 93–100%. Effectiveness was favoured by dry conditions after spraying, shade, infertile soils and non-grazing. Because of the variable results recorded, recommendation of a minimum effective rate for all regions cannot be made. The most practical method of determining this rate is for producers or researchers to apply a range of rates from 1.0 to 3.0 kg a.i. ha^{-1}, at 0.5 kg a.i. ha^{-1} intervals, over a number of years.

Results from aerial application of glyphosate indicated that it is effective in killing serrated tussock when applied by helicopter but at moderate and high rates trees would also be killed. The major disadvantage of glyphosate, damage to associated useful species, was reduced by applying it when the useful species were dormant. Overall spraying of serrated tussock in an introduced pasture resulted in re-infestation of 11 300 tussock seedlings ha^{-1} due to damage to the introduced species. To attempt to control these seedlings it would be necessary to re-sow the pasture after spraying.

Introduction

Flupropanate (Frenock®) proved an effective herbicide for selectively removing serrated tussock (*Nassella trichotoma* (Nees) Arech.) from introduced pastures, some native pastures and trees in Australia, South Africa and New Zealand (Campbell 1979, Campbell *et al.* 1979, Viljoen, 1987, Campbell and Ridings 1988) from 1978 until 1998. It was removed from sale in October 1998 and replaced with identical flupropanate products (Taskforce®, Kenock®) in late 2000. During the absence of Frenock® research for alternatives, which had been in progress before this (Campbell and Vere 1995), because the price of Frenock had increased from \$13 to \$35 L^{-1} between 1978 and 1998, was intensified. Of the herbicides tested pre-1998 glyphosate proved the most effective (Miller 1995, Campbell 1998a,b,c, Campbell *et al.* 1999). Despite its effectiveness glyphosate, has a number of disadvantages, the most serious being its variability in effect on serrated tussock and its non-selectivity. For example, the initial experiment that tested the effectiveness of glyphosate on serrated tussock (Campbell and Gilmour 1979) showed the highest rate used, 5 kg a.i. ha^{-1}, gave a maximum kill of only 81% whereas later research has shown that higher percentage kills can be obtained with rates as low as 0.9 kg a.i. ha^{-1} (Campbell *et al.* 1999, Miller 1999, Miller *et al.* 1999, Verbeek *et al.* 1999). In addition, whilst flupropanate could selectively remove serrated tussock from most introduced pastures and trees, glyphosate will kill almost all of these species. Thus further research was undertaken to examine the effect of time and rate of application of glyphosate on serrated tussock and methods of improving its selectivity on associated introduced species. Further research was also undertaken to test in the field the effect of new herbicides not already tested on serrated tussock and herbicides that had shown promise in killing serrated tussock in pot trials in the glasshouse/shadehouse (Melland 1997, Melland and McLaren 1998, Pritchard and Bonilla 1999).

Material and methods

Sites

Experiments were carried out near Tuena in the north of the southern tablelands of New South Wales (NSW) and near Berridale in the south. The altitude of the sites varied from 480 to 700 m at Tuena to 840 m at Berridale. Most experiments at the Tuena site and all experiments at Berridale were conducted on mature serrated tussock growing on infertile soil derived from slate. At Tuena three experiments were conducted on mature serrated tussock growing on fertile soil derived from andesite. No pasture improvement had been undertaken at Tuena but at Berridale the paddock had been cultivated and sown to subterranean clover *Trifolium subterraneum* cv. Goulburn, white clover *T. repens* cv. Haifa, phalaris *Phalaris aquatica* cvs Australian and Sirosa, cocksfoot *Dactylis glomerata* cv. Currie and fescue *Festuca arundinacea* cv. Triumph with superphosphate in March 1994.

Methods

In the small-plot (4 × 5 m) experiments herbicides were applied in 500 L ha^{-1} water with 0.5 L ha^{-1} of a non-ionic surfactant (added to all herbicides except flupropanate) from a hand-held pneumatic sprayer. Plots were arranged in randomized blocks with three or four replications. In the large unreplicated experiment, herbicides were applied by helicopter. Effect of treatments was measured by counting the number of tussocks per plot before and after treatment. No rain was recorded for at least 12 hours after each spraying. Results of individual experiments were analysed by analysis of variance.

Experiments 1, 2 and 3. Alternative herbicides

Experiments 1 and 2 were set down at Tuena on, respectively, 10 September 1998 and 27 November 1998, to test the efficacy of different rates (Tables 1 and 2) of herbicides (imazapyr, Arsenal®; propaquizafop, Correct®; glyphosate trimesium salt, Touchdown®; imazapic, Flame®; clethodim, Select®; butroxydim, Falcon®; AC299263) that had shown promise in killing serrated tussock in glasshouse experiments (Melland and McLaren 1998, Pritchard and Bonilla 1999) and other herbicides (rimsulfuron, Titus®; hexazinone, Velpar®; Non Tox®) that were possible grass killers. Results for experiments 1 and 2 were recorded, respectively, on 26 June 1999 and 28 October 1999.

Experiment 3 examined the effect of four rates of atrazine (0.9, 1.8, 3.6, 5.4 kg a.i. ha^{-1}) applied to serrated tussock at Tuena in each season of the year (same dates and conditions as in experiment 4). Results were recorded on 22 April 2000.

The serrated tussock on the experiment sites was recovering, during the favourable years of 1998 and 1999, from the drought from October 1997 to March 1998 (199 mm). At spraying on 10 September 1998 tussocks were 20 cm high (range 10–35 cm) and had 60% green leaf and no sign of seedhead emergence. The centre of each tussock was dead but regrowth from the circumference was vigorous. At spraying on 27 November 1998 the mean height was 25 cm (range 15–40 cm) with 80% green leaf and seedheads beginning to elongate (30% ground cover of seedheads). Condition of serrated tussock at spraying in experiment 3 was the same as that in experiment 4.

Experiment 4. Time and rate of application of glyphosate

Five rates of glyphosate (Table 3) were applied to serrated tussock at Tuena in each season of the year: spring, 21 October 1997; summer, 3 February 1998; autumn,

Table 1. Effect of herbicides applied on 10 September 1998 at Tuena in killing serrated tussock. Results recorded 26 June 1999.

Herbicide	Rate (ha^{-1}) (kg a.i.)	(product) L	(product) kg	Kill (%)
Glyphosate isopropylamine salt (Roundup Xtra® 49% a.i.)	2.94	6.0		100 a[A]
	1.96	4.0		100 a
	0.98	2.0		91 a
Glyphosate trimesium salt (Touchdown® 40% a.i.)	2.40	6.0		100 a
	1.60	4.0		100 a
	0.80	2.0		95 a
	0.40	1.0		40 bc
Flupropanate (Frenock® 75% a.i.)	1.12	1.5		91 a
Propaquizafop (Correct® 10% a.i.)	1.00	10.0		50 b
	0.80	8.0		50 b
	0.60	6.0		10 de
	0.40	4.0		3 e
	0.20	2.0		10 de
	0.10	1.0		7 e
	0.05	0.5		12 de
Rimsulfuron (Titus® 25% a.i.)	0.25		1.00	43 bc
	0.20		0.80	40 bc
	0.15		0.60	15 de
	0.10		0.40	13 de
	0.05		0.20	28 cd
	0.02		0.08	12 de
	0.01		0.04	10 de
Hexazinone (Velpar® 25% a.i.)	1.00	4.0		28 cd
	0.50	2.0		17 de
	0.25	1.0		3 e
Non Tox®	2000	2000		12 de
	1000	1000		14 de
	500	500		10 de
Control				3 e

[A] Values not followed by a common letter differ significantly P<0.05.

Table 2. Effect of herbicides applied on 27 November 1998 at Tuena in killing serrated tussock. Results recorded 28 October 1999.

Herbicide	Rate (ha^{-1}) (kg a.i.)	(product) L	(product) kg	Kill (%)
Flupropanate (Frenock® 75% a.i.)	1.31	1.75		100 a[A]
	1.12	1.50		100 a
	0.94	1.25		100 a
	0.75	1.00		100 a
	0.56	0.75		97 a
Glyphosate isopropylamine salt (Roundup Xtra® 49% a.i.)	3.23	6.60		100 a
	2.70	5.50		99 a
	2.16	4.40		98 a
	1.62	3.30		90 b
	1.08	2.20		50 e
Imazapyr (Arsenal® 25% a.i.)	0.75	3.0		100 a
	0.62	2.5		100 a
	0.50	2.0		80 c
	0.37	1.5		61 d
	0.25	1.0		25 g
Imazapic (Flame® 24% a.i.)	0.96	4.0		78 c
	0.72	3.0		76 c
	0.48	2.0		18 gh
	0.24	1.0		0 i
AC 299263 (Imazamox® 70% a.i.)	1.40		2.00	55 de
	0.70		1.00	40 f
	0.53		0.75	12 h
	0.35		0.50	3 i
	0.17		0.25	0 i
Clethodim (Select® 24% a.i.)	1.20–0.48	5.0–2.0		0 i
Butroxydim (Falcon® 25 % a.i.)	2.00–0.06	8.00–0.25		0 i
Control				0 i

[A] Values not followed by a common letter differ significantly P<0.05.

1 May 1998; winter 17 August 1999. Serrated tussock was growing vigorously in spring with 80% green leaves and no seedhead emergence. In summer and autumn the tussocks had only 30% green tissue because of drought conditions. In winter the tussocks had recovered from the drought and had 70% green tissue. Results were recorded on 22 April 2000.

Experiments 5 to 8. Effect of low rates of glyphosate
Low rates of glyphosate (Table 4) were applied to serrated tussock in four experiments at Tuena with the aim of restricting seedhead production but because of the unexpectedly high percentage kills recorded in some of the experiments the results give a more sensitive measure of the effect of glyphosate than experiment 4 where higher rates were used. In three small-plot experiments glyphosate was applied to serrated tussock before seedhead emergence (1 November 1995, 24 October 1997, 8 October 1998). In the large-plot experiment glyphosate (Table 4) was applied to serrated tussock after seedheads had emerged 15 cm on 5 November 1998 by a Hughes 500 helicopter in 30 L ha^{-1} of water using D6 nozzles with 45 swirl plates which gave a median droplet size of 350 microns. Plots of 5 ha were sprayed between 2 and 3 pm at 23°C with a variable breeze of 1 to 2 knots. Rainfall before and after spraying is recorded in Table 4. Results were recorded one year after spraying.

Experiments 9 to 11. Effect of soil fertility
On three occasions (Table 5) glyphosate was applied to serrated tussock growing on fertile soil derived from andesite and infertile soil derived from shale at Tuena. The two sites were 1.6 km apart at altitudes of 700 m (infertile) and 480 m (fertile). The fertile soil had a pH ($CaCl_2$) of 5.2, phosphorous of 10.3 mg g^{-1} (Bray No. 1) and exchangeable cations (Ca, Mg, K, Na, Al, cmol(+)kg^{-1} $BaCl_2$) of, respectively, 15.7, 3.8, 1.5, 0.1, 0.1. The respective values for the infertile soil were: pH 4.0, P 4.7, Ca 8.7, Mg 2.4, K 0.7, Na 0.1, Al 0.1. Results were recorded one year after spraying.

Experiment 12. Effect of shade
Four rates of glyphosate (Table 6) were applied to serrated tussock growing vigorously under favourable conditions at Tuena on 15 October 1997. Two replications were in the shade of *Casuarina cunninghamiana* trees and two were in an unshaded area 100 m away. Results were recorded on 22 December 1999.

Experiments 13 and 14. Selectivity
Herbicides were applied to two contiguous experiments at Berridale (Table 7), one on 18 March 1998 and one on 16 October 1998, to an introduced pasture sown in March 1994 (see Materials and methods) with re-infesting serrated tussocks. The March 1998 application was made in a drought (117 mm of rain in six months before spraying) when the introduced pasture was grazed heavily and almost dormant. Serrated tussock plants were 3.6 years old at a density of 60 plants 20m^{-2}. They had been grazed to a point 20 cm high with 40% of each tussock eaten. However the remaining butts of each tussock had 60% green leaf. Annual species

were dormant and the sown grasses almost dormant (2% ground cover of green leaf; 21 plants 20m^{-2} with the odd green leaf).

In October 1998, the pasture and tussock were sprayed when growing under favourable conditions (264 mm of rain in six months before spraying). The ungrazed serrated tussock plants were 4.2 years old with 90% green leaf, 25 cm high at a density of 68 per 20m^2. Ground cover of pasture species was: subterranean clover 40%, sown grasses 15%, other species 5%, bare ground 20% and serrated tussock 20%.

Percentage kill of serrated tussock and seedling reinfestation were calculated from whole plot counts at spraying and at measurement on 11 November 1999. Ground cover of pasture species was visually estimated.

Results

Experiments 1, 2 and 3. Alternative herbicides

At the rates applied, only glyphosate (isopropylamine or trimesium salts) and imazapyr exhibited similar efficiency to flupropanate in killing serrated tussock (Tables 1 and 2).

Atrazine was ineffective (maximum kill 10%) at any of the times or rates applied (results not presented). At high rates of atrazine (3.6 and 5.4 kg a.i. ha^{-1}), up to 80% brown out occurred but almost all plants recovered.

Experiment 4. Time and rate of application of glyphosate

Time of spraying only had an influence on efficiency of glyphosate at the lowest rate (0.9 kg a.i. ha^{-1}); application in summer and autumn being more ($P<0.05$) effective than application in winter or spring (Table 3). High rates of glyphosate were more effective than low rates when meaned for time of application.

Experiments 5 to 8. Effect of low rates of glyphosate

When applied in spring in 1995, 1997 and 1999 at Tuena the effect of low rates of glyphosate varied from 0 to 96 % kill of serrated tussock at 0.45 to 0.49 kg a.i. ha^{-1} and from 0 to 81% at 0.225 to 0.245 kg a.i. ha^{-1} (Table 4). Application of a low rate (0.735 kg a.i. ha^{-1}) from a helicopter in spring 1998 resulted in a high percentage kill (Table 4) indicating that this method of spraying could be effective in hill country.

Experiments 9 to 11. Effect of soil fertility

At low rates, glyphosate was more effective in killing serrated tussock growing on infertile soil than tussock growing on fertile soil (Table 5). As the rate of glyphosate increased the differential in percentage kill between soil types disappeared.

Experiment 12. Effect of shade

At low rates, glyphosate was more effective in killing serrated tussock growing in the shade than in full sunlight (Table 6). At higher rates there was no difference in effect between shaded or unshaded situations.

Experiments 13 and 14. Selectivity

Table 3. Effect of time and rate of application of glyphosate on kill (%) of serrated tussock at Tuena.

Time of application	Rate of glyphosate (kg a.i. ha^{-1})				
	0.9	1.8	2.7	3.6	4.5
Spring 1997	21 d[A]	85 abc	98 ab	96 ab	99 a
Summer 1998	75 c	90 abc	99 ab	100 a	100 a
Autumn 1998	81 bc	90 abc	94 ab	99 a	99 a
Winter 1999	25 d	84 abc	88 abc	94 ab	100 a
Mean	53 C[B]	87 B	94 AB	97 A	99 A

[A] Values not followed by a common lower case letter differ significantly $P<0.05$.
[B] Means not followed by a common upper case letter differ significantly $P<0.05$.

Table 4. Effect of low rates of glyphosate on kill (%) of serrated tussock at Tuena.

Rate (kg a.i. ha^{-1})	Rate (L ha^{-1} product)		Time of spraying: 1 November 1995	24 October 1997	8 October 1998	5 November 1998 (aerial)
0	0		0 a[A]	0 c	8 c	1[B]
0.225–0.245	0.46–0.50		0 a	12 b	81 b	11
0.337	0.69			22 b		
0.450–0.490	0.92–1.00		0 a	57 a	96 a	54
0.675–0.735	1.38–1.50		0 a			82
0.900–1.080	1.84–2.20				99 a	
			Rainfall (mm month^{-1})			
Before spraying		1	50	26	80	111
		2	138	107	76	58
		3	18	52	158	120
After spraying		1	146	32	87	69
		2	115	57	65	30
		3	75	30	30	11

[A] Values in columns not followed by a common letter differ significantly $P<0.05$.
[B] Unreplicated aerial experiment.

Table 5. Effect of glyphosate on kill (%) of serrated tussock growing on infertile and fertile soil at Tuena.

Rate		Time of application: 1 May 1998		17 August 1998		12 October 1999	
(kg a.i. ha^{-1})	(L ha^{-1})	Infertile	Fertile	Infertile	Fertile	Infertile	Fertile
0.45	1					70 b	20 c
0.90	2	92 a[A]	60 c	45 d	5 e	96 a	30 c
1.35	3					99 a	57 b
1.80	4	98 a	75 b	90 ab	77 c		
2.70	6	97 a	80 b	89 abc	82 bc		
3.60	8	98 a	97 a	93 ab	94 a		

[A] Values for each time of application not followed by a common letter differ significantly $P<0.05$.

Table 6. Effect of glyphosate on kill (%) of serrated tussock growing in shaded or unshaded situations at Tuena.

Rate of glyphosate kg a.i. ha^{-1}	L ha-^{1}	+ shade	- shade
0	0	0 c[A]	0 c
0.9	2	63 b	0 c
1.8	4	95 a	75 b
2.7	6	99 a	92 a
3.6	8	99 a	96 a

[A] Values not followed by a common letter differ significantly $P <0.05$.

Table 7. Effect of herbicides on kill of serrated tussock when applied on 18 March 1998 and 16 October 1998 to serrated tussock growing amongst, respectively, dormant and active pasture at Berridale. Results recorded on 11 November 1999.

Herbicide and rate		Kill of serrated tussock (%)	
(kg a.i. ha^{-1})	(L ha^{-1})	Dormant	Active
Glyphosate			
0	0	0 c[A]	0 c
0.22	0.50	0 c	73 b
0.45	1.00	19 bc	91 a
0.90	2.00	29 b	86 ab
1.80	4.00	20 bc	95 a
2.70	6.00	19 bc	98 a
3.60	8.00	36 b	99 a
Flupropanate			
0.75	1.00	94 a	na
0.94	1.25	97 a	na

[A] Values in columns not followed by a common letter differ significantly P<0.05.
na = not applied.

Table 8. Effect of herbicides on ground cover of pasture species when applied on 18 March 1998 and 16 October 1998 to serrated tussock growing amongst, respectively, dormant and active pasture at Berridale. Results recorded on 11 November 1999.

Herbicide (kg a.i. ha^{-1})	Ground cover (%)							
	Dormant				Active			
	Sub clover	Sown grasses[A]	Bare	Mature tussock	Sub clover	Sown grasses[A]	Bare	Mature tussock
Glyphosate (45% a.i.)								
0	18 b[B]	17 a	18 a	48 a	18 a	16 a	18 d	48 a
0.245	20 b	21 a	17 a	40 ab	18 a	4 b	42 c	6 b
0.490	22 b	17 a	12 a	23 cd	18 a	3 b	45 c	3 b
0.980	27 ab	13 a	7 a	31 bc	15 a	1 b	50 bc	3 b
1.960	27 ab	15 a	15 a	22 cd	12 a	1 b	50 bc	1 b
2.940	27 ab	15 a	15 a	22 cd	11 a	1 b	60 ab	1 b
3.920	33 a	19 a	18 a	16 d	12 a	0 b	63 a	1 b
Flupropanate (75% a.i.)								
1.0	33 a	22 a	12 a	1 e	na	na	na	na
1.25	32 a	20 a	13 a	1 e	na	na	na	na

[A] Phalaris, cocksfoot, fescue.
[B] Values in columns not followed by a common letter differ significantly P<0.05.
na = not applied.

Table 9. Comparison of the effect of herbicides on serrated tussock in pot trials in glasshouses and in the field.

Herbicide	Glasshouse		Field	
	Rate (kg a.i. ha^{-1})	Kill (%)	Rate (kg a.i. ha^{-1})	Kill (%)
AC299263	0.05	100[A]	1.40	55
Glyphosate	1.08	99[A]	1.08	50–99
Imazapyr	0.25	99[A]	0.25	25
Touchdown®	0.41	97[A]	0.40	40
Propaquizafop	0.12	80[A]	1.00	50
Atrazine	2.00	17[A]	5.40	10
Clethodim	1.00	99[A]	1.00	20
Clethodim	0.09	100[B]	1.00	20

[A] Melland (1997).
[B] Pritchard and Bonilla (1999).

Glyphosate was more effective in killing serrated tussock when applied in October 1998 to ungrazed actively growing tussocks with 90% green leaf than when applied in March 1998 to tussocks grazed to a point and affected by drought (Table 7). In contrast, flupropanate was effective in killing serrated tussock when applied to grazed tussock in the dry conditions of March 1998.

Application of glyphosate to actively growing pasture in October 1998 resulted in a severe reduction in ground cover of sown grasses, a slight reduction in subterranean clover, and a large increase in bare ground 13 months after spraying (Table 8). Application of glyphosate or flupropanate in dry conditions in March 1998 had little effect on the ground cover of sown species. Competition from serrated tussock on the control in the March 1998 experiment restricted subterranean clover and sown grasses.

Seedling regeneration of serrated tussock after spraying with glyphosate was higher on the plots sprayed in October 1998 (11 300 ha^{-1}) than those sprayed in March 1998 (700 ha^{-1}). Only 75 seedlings ha^{-1} reinfested after spraying with Frenock in March 1998.

Discussion

The effectiveness of herbicides in killing serrated tussock showed a marked disparity between experiments in the field and pot trials in the glasshouse (Table 9). For each herbicide tested percentage kill was lower in the field than in the glasshouse. Tussocks in the glasshouse tests were smaller (grown in 12–15 cm diameter pots) than those in the field and thus proved more susceptible to herbicides than mature tussocks in the field.

Of all the alternatives to flupropanate tested, the only two that yielded commercially acceptable kills of serrated tussock were imazapyr and glyphosate. Although imazapyr, at the rates used, will not kill phalaris and subterranean clover (Campbell unpublished data) it will kill many tree species (Anon. 1991) and, as the recommended retail price in 1999 was \$90 L^{-1}, its commercial use is unlikely. Therefore the best alternative to flupropanate is glyphosate, with the added advantage that it is relatively cheap (\$8 L^{-1}).

If glyphosate is to be used the optimum time and rate of application must be determined. In experiment 4, time of application only had an effect at the lowest rate of 0.9 kg a.i. ha^{-1}; here application in autumn and summer gave higher (P<0.05) kills than in spring and winter. In an earlier experiment in Australia, time of application did not influence the effectiveness of glyphosate applied at 1.0, 3.0 and 5.0 kg a.i. ha^{-1} (Campbell and Gilmour 1979). In an experiment in South Africa where four rates of glyphosate were applied in each month of the year there was no clear pattern in effect of time of application. For example, 2.16 kg a.i. ha^{-1} was effective (>94% kill) in February, April, August, October and November, moderately effective (80–90% kill) in March, May, June and September but ineffective in January, July and December (Viljoen 1981). These results show that there is insufficient evidence to indicate the optimum time of application. Avoiding application in late spring and summer when the tussocks are covered with seedheads appeals as a wise precaution. Other factors such as environment (soil fertility, rainfall, shade), pretreatment (grazing) and ecotype may have more influence on the optimum rate of glyphosate necessary to kill serrated tussock than time of application.

Experiments 9 to 11 demonstrated that glyphosate was more effective in killing serrated tussock growing on infertile soil than tussock on fertile soil (Table 5). Flupropanate and 2,2-DPA are also more effective in killing serrated tussock on infertile soils derived from slate, shale and granite than on fertile soils derived from basalt and andesite (Campbell 1998c).

Results from the application of low rates designed to prevent seedhead production in experiments 5 to 8 showed that if dry conditions follow spraying, glyphosate may be effective at lower rates than if high rainfall is received. For example, low rates applied in springs 1997 and 1998 gave unexpectedly high kills (up to 96%) under dry conditions in the three months after spraying (respectively 119 and 182 mm rain) whereas the same low rates when applied in wetter conditions in spring 1995 (336 mm in the three months after spraying) yielded 0% kill (Table 4). Adequate soil moisture should be present at spraying (as occurred in these experiments, Table 4) to favour translocation of glyphosate to the sinks in the plant (Franz *et al.* 1997) but dry conditions after this that inflict severe moisture stress on serrated tussock could assist glyphosate. Whether rainfall will be low after spraying cannot be known at spraying, therefore this factor cannot be used to maximize the effectiveness of glyphosate unless long-term forecasts become reliable.

In experiment 12, glyphosate proved more effective in killing serrated tussock in shade than in direct sunlight. Plants grown under low light intensity generally produce less epicuticular wax and absorb more glyphosate than plants grown under high light intensities (Kirkwood 1983). Low light levels produce plants with a high ratio of foliage to propagules, which are more readily controlled by glyphosate (Franz *et al.* 1997). As other factors could also be involved, such as competition for moisture and nutrients between the trees and the weed, further research should examine the effect of shade without other influences. If shade is proven to assist the efficiency of glyphosate, then maximum effect could be achieved by applying lower rates in winter, in the lower latitudes in Australia or to the eastern and southern aspects of hills.

Grazing prior to spraying could also influence the effectiveness of glyphosate. For example, the poor results from the March 1998 spraying in experiment 13 could have been due to the tussocks being heavily grazed to a point which restricted coverage. Regrowth after this spraying occurred from the uphill side of the tussocks indicating that the grazed short green leaves on the uphill side did not receive glyphosate. It is well known for most perennial grasses that a minimum amount of foliage is required for a satisfactory kill with glyphosate (Franz *et al.* 1997). Grazing or burning to reduce foliage below this minimum level could reduce effectiveness.

Variation in the effectiveness of glyphosate could be explained by different ecotypes varying in their susceptibility. Evidence that different ecotypes exist has recently been presented. Campbell (1998b) noted differences in the morphology of seedlings from NSW and Victoria and S. Casonato (personal communication 2000) found the morphologies of mature plants from NSW and Australian Capital Territory to differ significantly from those of plants from Victoria and Tasmania.

Method of application did not appear to influence the effectiveness of glyphosate in this project. In the small-plot experiments glyphosate was applied in 500 L ha^{-1} of water from plant-top height to ensure an even coverage on steep slopes scattered with rocks, logs and depressions. In the aerial spraying, glyphosate was applied in 30 L ha^{-1} of water from 5 m to 20 m height. Glyphosate was effective from both levels of dilution and both methods of application.

In the aerial sprayed experiment a low rate of glyphosate (0.735 kg a.i. ha^{-1}) gave an unexpectedly high kill (82%) of serrated tussock under perceived favourable conditions (dry after spraying). Leaves on *Eucalyptus blakelyii* were scorched by this rate but the trees completely recovered. However, as experiments in this project indicate that much higher rates of glyphosate will be necessary to kill serrated tussock under less favourable conditions, damage to trees would be severe and thus aerial application would only be practicable where trees were widely scattered or absent. As this was the first recorded aerial application of glyphosate to serrated tussock in NSW further testing in other environments is necessary before recommendations can be made.

The above discussion shows that the minimum effective rate of glyphosate can vary between 0.45 and >5.0 kg a.i. ha^{-1} (i.e. 0.9 to >10.2 L ha^{-1} of the 49% a.i. product) depending on time of application, environmental conditions and pre-treatment. As variation in effectiveness declines with increasing rate, applying a high rate could give reliable results under most conditions. However this would not be the most economic rate and would cause more off-target damage than the lowest effective rate. The most practical method of determining the minimum effective rate is for producers to apply a range of rates on their properties (Campbell *et al.* 1999). However as so many variables influence the effectiveness of glyphosate, experimentation is needed over a number of years to yield reliable results. From the evidence available at present, the most likely rates that could prove effective would be 1.0, 1.5, 2.0, 2.5 and 3.0 kg a.i. ha^{-1}. Low rates could be considered when, ungrazed serrated tussock with no seedheads and no frost or drought damage, growing actively on infertile moist soil on shady hillsides was sprayed in the hotter/drier months of the year. Higher rates than those suggested above would have to be considered where serrated tussock was growing in fertile soil in high rainfall areas. At present permits have been issued by the National Registration Authority to cover rates of glyphosate for boom spraying from 2.16 to 5.4 kg a.i. ha^{-1} (Dellow 1998).

Effect on pasture species

When applied to an actively growing introduced pasture in October 1998 at Berridale, rates of glyphosate from 0.245 to 3.92 kg a.i. ha^{-1} severely affected phalaris, cocksfoot and fescue. Similar deleterious effects resulted from application of low rates of glyphosate to phalaris on the central tablelands in spring 1986 (54% reduction in ground cover with 0.54 kg a.i. ha^{-1}, Campbell and Ridings 1988) and spring 1988 (66% reduction in ground cover with 0.32 kg a.i. ha^{-1}, Campbell and Nicol 1991). These deleterious effects can be reduced by applying glyphosate when phalaris is dormant or by grazing heavily before spraying (Campbell and Ridings 1988). However not all phalaris cultivars can be saved by grazing before spraying. For example, Australian commercial phalaris produces many small leaves when grazed heavily and thus is susceptible to glyphosate whereas heavy grazing removes almost all green leaf from Sirosa phalaris which renders it tolerant. Other introduced pasture grasses are just as susceptible to glyphosate as phalaris whereas subterranean clover is slightly more tolerant. In annual pastures selectivity can be achieved if glyphosate is applied when they are dormant. Native grasses tolerate glyphosate when they are heavily frosted. However to spare both is difficult because native grasses are generally active in summer when annuals are dormant and annuals are active in winter when some native grasses are frosted.

Regeneration of seedling tussock

The effect of glyphosate in destroying pasture species after spraying in October 1998 at Berridale resulted in massive regeneration of serrated tussock seedlings which agrees with practical experience over the past 20 years. Fewer seedlings regenerated after application of glyphosate in March 1998 than in October 1998 because dormant pasture species were not destroyed by the March spraying. Flupropanate controlled regeneration of tussock seedlings after the March 1998 application due to its residual effect. When glyphosate is used to kill serrated tussock consideration should be given to sowing improved species and applying fertilizer after spraying in an effort to minimize seedling regeneration (Campbell 1995). When spot spraying, a shield over the nozzle should be used to reduce glyphosate damage.

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References

Anon. (1991). 'Arsenal herbicide', pp. 20. (Cyanamid Co, Princeton, USA).

Campbell, M.H. (1979). Selective removal of *Nassella trichotoma* from a *Phalaris aquatica* pasture. Proceedings 7th Asian-Pacific Weed Science Society Conference, Sydney, pp. 129-30.

Campbell, M.H. (1998a). Review of the effects of glyphosate on serrated tussock. Proceedings 1st Conference on Alternative Herbicides for Serrated Tussock Control, NSW Agriculture, Albury, pp. 1-11.

Campbell, M.H. (1998b). Biological and ecological impact of serrated tussock (*Nassella trichotoma* (Nees) Arech.) on pastures in Australia. *Plant Protection Quarterly* 13, 80-6.

Campbell, M.H. (1998c). Use of low rates of herbicides to control serrated tussock, African lovegrass and St. John's wort in NSW. Proceedings 13th Conference Grassland Society of NSW, Orange, 13, pp. 85-8.

Campbell, M.H. (1995). Serrated tussock control. NSW Agriculture Agfact P7.6.30., pp. 7.

Campbell, M.H. and Gilmour, A.R. (1979). Effect of time and rate of application of herbicides on serrated tussock (*Nassella trichotoma*) and improved pasture species. 1. Glyphosate and 2,2-DPA. *Australian Journal of Experimental Agriculture and Animal Husbandry* 19, 472-5.

Campbell, M.H., Gilmour, A.R. and Vere, D.T. (1979). Effect of time and rate of application of herbicides on serrated tussock (*Nassella trichotoma*) and improved pasture species. 2. Flupropanate. *Australian Journal of Experimental Agriculture and Animal Husbandry* 19, 476-80.

Campbell, M.H., Miller, L.G. and Michalk, D.L.(1999). Alternatives to flupropanate for the control of serrated tussock. Proceedings 12th Australian Weeds Conference, Hobart, pp. 526-8.

Campbell, M.H. and Nicol, H.I. (1991). Tolerance of *Phalaris aquatica* to spraytopping rates of glyphosate or paraquat. *Australian Journal of Experimental Agriculture* 31, 229-31.

Campbell, M.H. and Ridings, H.I. (1988). Tolerance of grazed and ungrazed *Phalaris aquatica* to glyphosate, tetrapion and 2,2-DPA. *Australian Journal of Experimental Agriculture* 28, 747-51.

Campbell, M.H. and Vere, D.T. (1995). *Nassella trichotoma* (Nees) Arech. *In* 'The Biology of Australian Weeds' Volume 1, eds R.H. Groves, R.C.H., Shepherd, and R.G. Richardson, pp. 189-202. (R.G. and F.J. Richardson, Melbourne, Victoria).

Dellow, J.J. (1998). Serrated tussock control. NSW Agriculture Agnote DAI/75, pp. 3.

Franz, J.F., Mayo, M.K. and Sikorski, J.A. (1997). Glyphosate a unique global herbicide. American Chemical Monograph 189. American Chemical Society, Washington.

Kirkwood, R.C. (1983). Effect of glyphosate as influenced by shade. *Pesticide Research* 14, 453-60.

Miller, L. (1995). The use of Roundup® on serrated tussock. Proceedings Grassland Society of Victoria, pp. 195-6.

Miller, L. (1999). Serrated tussock experiments 1994–96. Department of Natural Resources and Environment, Geelong, Victoria, pp. 8.

Miller, L., Wilsher, M. and Boyle, D. (1999). The use of glyphosate on serrated tussock. Department of Natural Resources and Environment, Geelong, Victoria, pp. 48.

Melland, A. (1997). Efficacy of herbicides against serrated tussock (*Nassella trichotoma)* in a pot trial. Thesis for B.Sc.Agr. University of Melbourne, pp. 34.

Melland, A. and McLaren, D. (1998). Efficacy of herbicides against serrated tussock (*Nassella trichotoma*) in a pot trial. *Plant Protection Quarterly* 13, 102.

Pritchard, G.H. and Bonilla, J. (1999). Efficacy of herbicides on serrated tussock in pot trials. Proceedings 12th Australian Weeds Conference, Hobart, pp. 165-8.

Verbeek, B., Milne, B.R., Ayres, L., Leech, F.J., Booth, J. and Gorman, R. (1999). Serrated tussock (*Nassella trichotoma*) control using glyphosate in the southern tablelands of NSW. Proceedings 10th Biennial Noxious Weeds Conference, Ballina, pp. 71-5.

Viljoen, B.D. (1981). Application of glyphosate on nassella (*Stipa trichotoma)* at different times and rates. *Crop Production* 10, 206-8.

Viljoen, B.D. (1987). Effect of rate and time of application of tetrapion on nassella tussock (*Stipa trichotoma*) in South Africa. *South African Journal of Plant and Soil* 4, 79-81.