# Using plant development to determine optimum times for spraytopping, and assessing effect of grazing and double/repeat herbicide applications on regeneration of vulpia

**P.M. Dowling**[AB], **G.D. Millar**[B], **B. Milne**[BC] and **P. Newell**[BD]
[A] Charles Sturt University PO Box 883, Orange, New South Wales 2800, Australia.
[B] New South Wales Department of Primary Industries, Orange Agricultural Institute, Forest Road, Orange, New South Wales 2800, Australia.
[C] Smith Street, Molong, New South Wales 2866, Australia.
[D] Belubula Way, Canowindra, New South Wales 2804, Australia.

## Summary
**Control of vulpia, an annual grass weed of temperate Australian pastures, has relied on spraytopping in spring using sublethal rates of paraquat and glyphosate; and wintercleaning using simazine. For spraytopping, the application window is narrow and a more accurate and practical procedure for assessing optimum application times is required. This was examined in replicated field experiments on an annual pasture near Bathurst, NSW over three years where paraquat and glyphosate were applied on four occasions in each spring, and at each spray time, the stage of vulpia development recorded. Herbicide effectiveness was dependent on the proportion of tillers where the seedheads were visible (peeping), but varied with herbicide type. Control following glyphosate and paraquat was optimum at 70–80% peeping, and 80–90% peeping, respectively. Plant development was related to cumulative mean temperatures ($R^2$ = 0.83) and provides another option for assessment of optimum application times. For their respective optimum application times, glyphosate was more effective than paraquat in controlling vulpia, but regeneration of subterranean clover was lower. Marginally greater control of vulpia was achieved by doubling recommended application rates, repeating applications in successive years and applying grazing pressure following herbicide application. However, when assessed 18 months after spraytopping and with no other restrictions to natural seeding, vulpia populations had significantly increased, indicating that spraytopping needs to be complemented by other management inputs for long-term control.**

**Keywords: glyphosate, paraquat, subterranean clover.**

## Introduction
Annual grasses and forbs are well represented in the high rainfall zone (HRZ >650 mm AAR) of temperate Australia (Kemp and Dowling 1991, Quigley *et al.* 1992, Dellow *et al.* 2002), and the relative usefulness of these annual species depends on the presence/absence of more desirable perennial species. In permanent pastures in the HRZ, there is an increasing need to maintain the perennial component, especially grasses, but adverse seasons and inappropriate management strategies have resulted in a general decline in the perennial component and its replacement by annuals (e.g. Moore 1970). Reversing this trend requires ongoing management inputs, and successful strategies for achieving this have been developed (e.g. Michalk *et al.* 2003). Where the level of infestation by the annuals is great (as expressed in biomass), herbicide application may also need to be included as part of the management package.

Aryloxyphenoxypropionate and cyclohexanedione herbicides are highly effective in reducing most annual grasses in legume-based pastures, but are ineffective on vulpia (*Vulpia* spp. Leys *et al.* 1988). Reducing seed production and seedling regeneration of vulpia can be achieved by applying sub-lethal applications of glyphosate or paraquat in spring (spraytopping) (Leys *et al.* 1991a, Dowling *et al.* 1997), and/or simazine applied in winter ('wintercleaning' e.g. Leys *et al.* 1991b), but reductions are relatively short-term. However, effectiveness of herbicide application in reducing vulpia seedling regeneration, particularly for spraytopping, is highly dependent on application time (Leys *et al.* 1991a). Current spraytopping recommendations for paraquat are '…when all heads have emerged and there are initial signs of haying off', and for glyphosate, '…apply at head to milky dough stage, before haying off' (Dellow *et al.* 2003). The latter stage for vulpia especially, would be difficult to consistently determine because of the small caryopsis. Both guidelines are extremely broad, and while it is clear that glyphosate should be applied earlier than paraquat, guidelines remain vague and impractical.

It would seem then, that selecting criteria which can be quickly quantified in the field and have a plant physiological basis, would result in more reliable optimum application time for each herbicide. An earlier attempt to do this has been reported by Leys *et al.* (1991a), who used a formal plant growth code (Zadoks *et al.* 1974) as the basis for defining plant development. Stages assessed were 'approximately' when 75% of the plants were at 'heading', 'anthesis' and 'early grain filling', but it was not clear how these stages were assessed. Further, the ability to accurately define these stages for vulpia is extremely difficult in the field, given that visible signs of flowering are absent, and determination of the 'milky dough' or 'early grain filling' stages in a small elongated seed is not readily apparent with the naked eye. Using developmental stages that are more easily discernible in the field such as extent of tillering and head appearance/emergence might provide a more reliable assessment of plant development.

Another feature of previous studies on spraytopping was that the effectiveness of the technique was evaluated only a short time after application, often as early as six months after application (e.g. Leys *et al.* 1991a,b). Such a short time frame for evaluation would be expected to over emphasise its impact in subsequent seasons.

In a series of experiments over a three year period we examined the reliability of seed-head appearance as a guide to spraytopping in a field population of *Vulpia* spp. (predominately *V. bromoides* and *V. myuros*), the effectiveness of herbicide application, and the utility of combining management inputs on effectiveness in reducing seed production and seedling regeneration, both of which underpin vulpia's contribution to pasture composition.

## Materials and methods
The experiments were conducted on a commercial farm (33°28'S, 149°31'E; elevation 712 m) near Bathurst, New South Wales over the period 1988 to 1991.The experimental area was approx. 0.6 ha and fenced off from the larger surrounding paddock. Initial pasture composition as assessed in early spring 1988 by a 10-pin point quadrat was: vulpia (*Vulpia* spp.) 68%, other annual grasses 5%, native grasses 2%, annual legumes 16% and forbs 9%. Soil type was a free draining podsolic derived from granite, with a loamy sand texture. Soil pH ($CaCl_2$) and P (Olsen) levels sampled from an adjacent area in 1989 were 4.8 and 9.4, respectively. Climatic data were derived from 'Datadrill' over the period 1970 to 1999 (Jeffrey *et al.* 2001). Herbicides were applied at recommended 'spraytopping' rates (Dellow *et al.* 2003) in late spring.

These were: glyphosate (Roundup CT, 450 g $L^{-1}$ – 162 g a.i. $ha^{-1}$), and paraquat (Gramoxone W, 200 g $L^{-1}$ – 100 g a.i. $ha^{-1}$) unless otherwise indicated. Herbicides were applied in 100 L water per ha with wetting agent (Agral 600) using a LP gas powered bottle system and a 3 m boom. Spray drift was minimized with a mobile screen (2 × 1 m) placed on the leeward side of the boom.

Effectiveness of treatments was based on the extent of seedling regeneration in the following autumn/winter from intact soil cores collected in late summer following spray application. The number of cores collected depended on experiment and plot size. The soil cores (7.5 cm diameter, 10–12 cm deep) were placed outdoors in trays and regularly watered commencing in autumn to promote germination. Seedlings were identified and removed from each core after recording. Identified seedlings were recorded on 3–4 occasions over a six month period after which further significant germination was unlikely to occur. Seedlings were placed in the following groups for statistical analysis – vulpia, subterranean clover (*Trifolium subterraneum* L.), other grasses, other legumes, and forbs, and analyzed by GenStat (GenStat 2000) as seedlings $m^{-2}$.

*1. Optimum timing of spraytopping herbicide application*

This experiment compared spraytopping treatments with an unsprayed control over three years, and a heavily grazed treatment in the initial year. For each year, previously untreated land was used. Spraytopping treatments were applied at four different times over spring in 1988, 1989 and 1990. The timing of each herbicide application occurred during the late reproductive phase of vulpia. The appearance of the inflorescence through the flag leaf was easy to recognize, and development was ongoing over the period that both herbicides were likely to be effective. On that basis, inflorescence appearance was used as the criterion for assessing the reproductive development of the vulpia population. Development was qualitatively monitored by collecting grab samples of vulpia plants from 12–15 locations across the area to be treated. This process commenced around the start of tiller elongation. The percentage of tillers where inflorescences were visible were then calculated (% peeping). Herbicide application times were 2–6 days apart (Table 1). Treatments were laid out as a randomized block design with four replications. Plot dimensions were 10 m × 3 m.

Prior to the initial spraytopping in each year, the experimental area was lightly grazed (7.5 sheep dse $ha^{-1}$) sporadically over winter, and then lightly grazed until vulpia plants commenced elongation. After completion of seed maturation and seed shedding, the experimental area was again grazed at 150 dse $ha^{-1}$ on three occasions (each 2–4 days) over summer. In 1988, the 'grazed' plots were individually fenced, and were heavily grazed at 1000 dse $ha^{-1}$ for three periods (each two days) during the same period that herbicide was applied to the herbicide treated plots.

**Table 1. Timing of herbicide application together with degree of inflorescence development (% peeping) for each of the years where spraytopping was evaluated (1988, 1989, and 1990).**

| Year | | Application | | | |
|---|---|---|---|---|---|
| | | Time 1 | Time 2 | Time 3 | Time 4 |
| 1988 | Date of herbicide | 21 Oct | 27 Oct | 1 Nov | 7 Nov |
| | % peeping | 66 | 78 | 88 | 90 |
| 1989 | Date of herbicide | 26 Oct | 1 Nov | 3 Nov | 8 Nov |
| | % peeping | 60 | 83 | 87 | 95 |
| 1990 | Date of herbicide | 24 Oct | 26 Oct | 29 Oct | 31 Oct |
| | % peeping | 70 | 73 | 92 | 95 |

*2. Effect of herbicide rate*

This experiment also compared the effectiveness of double versus the recommended rates of glyphosate and paraquat. Herbicides were applied at the same four times as in the previous experiment in 1988, and effectiveness of treatments was based on the extent of seedling regeneration in the following autumn/winter from intact soil cores (four per plot) collected in late summer following spray application. Treatments were laid out as a randomized block design with four replications with plot dimensions 10 m × 3 m.

*3. Repeat spraytopping applications*

Repeat applications of the same herbicides were made in 1989 on selected treatments where vulpia regeneration was lowest in the optimum timing experiment in 1988. The lowest regeneration was similar for two application times for each herbicide. As a consequence, plots treated at both application times were used to assess the effect of reapplication. Each reapplication time was based on two replicates. Reapplication of the recommended rate for glyphosate was at Time 1 (Table 1) and at Time 2, whereas for paraquat, reapplication was at Time 2 and at Time 3. Prior to reapplication in 1989, all plots to be treated were randomly split into two subplots – one half where the herbicide was reapplied; and the other half used as the control (nil herbicide reapplication) to evaluate the effectiveness of the repeat application. Seedling regeneration was recorded from two soil cores per subplot.

Data from both years were combined to give eight treatments (see Figure 3 in results section).

*4. Grazing vs. resting following spraytopping*

This comparison was evaluated in a split plot design where plus or minus grazing were the main plots. Grazing was blocked across two replicates and adjacent to the rested block for ease of fencing. The three herbicide treatments were sub-plots (each 10 × 3 m) and were allocated randomly within each replicate block. The herbicides were glyphosate and paraquat applied close to their respective optimum application times (88% peeping) at the recommended rates (see rates above), and an unsprayed control. For the other two replicates, the grazed and rested blocks were spatially alternated. Each 'grazed' block was individually fenced. Treatments were applied in spring1988 and evaluated in 1989. Grazing on the 'grazed' plots commenced 10 days after herbicide application (560 dse $ha^{-1}$ for two days on three occasions over a two week period), while grazing on the 'rested' plots was resumed after seed had matured and then grazed as for the 'grazed' plots (see previous section for grazing details). Effectiveness of treatments was evaluated by comparing vulpia seedling regeneration from intact soil cores (four cores per subplot) collected in late summer 1989.

## Results

*Climate*

Monthly rainfall in all years of the experiments was well above average (Figure 1) in early autumn (March 1989; and April all years), and was average or above average for the remainder of autumn and over winter. Spring rainfall was below average in October for all years; below average in September for 1989 and 1990; and below average in November 1990.

Average monthly maximum temperatures were similar from January to June for all years of the experimental period; were lower in July and August 1989 and 1990; higher in October 1988; and higher in December 1990 (Figure 1). The rate of increase in average monthly maximum temperature after August was greater in 1990. Average monthly minimum temperatures tended to differ across years, but not consistently. Spring minimum temperatures tended to be higher in 1988, lower in 1989, and intermediate in 1990.

The pattern of daily temperature increases around the time of herbicide application varied for each of the three years. For 1990 from 21 to 31 October, daily maximum temperature increased rapidly from 13.7 to 30°C, an increase of almost 1.5°C day$^{-1}$. Over the same period, daily maximum temperature actually declined in 1988 after abnormally high temperatures on 21, 22 October, but thereafter increased at a greater rate for a shorter period (1.7°C day$^{-1}$ over seven days). In 1989, daily maximum temperatures increased at a slower rate over the same period, but over shorter periods, temperature increase was extremely rapid. No discernible patterns across years were evident for daily minimum temperatures (data not shown).

*Seedling regeneration*

**1. Optimum timing of spraytopping herbicide application** Rate of vulpia plant development differed between years, with development fastest in 1990 (95% peeping by October 31 – Table 1) Overall, herbicide and heavy grazing significantly (P <0.001) reduced vulpia regeneration compared to the control (Figure 2a). Glyphosate (P <0.05) reduced vulpia regeneration slightly more than paraquat (glyphosate – 7060 plants m$^{-2}$, paraquat – 7520 plants m$^{-2}$), but the time of application influenced the effectiveness of the herbicide (P <0.001). Glyphosate was more effective (P <0.001) when applied earlier, while paraquat was more effective (P <0.001) with application at Time 4.

Overall, glyphosate significantly (P <0.01) reduced subterranean clover regeneration compared to paraquat, heavy grazing and control. Of the herbicides, glyphosate significantly (P <0.01) reduced seedling numbers more than paraquat (glyphosate – 1130 plants m$^{-2}$; paraquat – 1700 plants m$^{-2}$). Time of herbicide application influenced this effect (Figure 2b) with glyphosate at Time 2 having the lowest subterranean clover regeneration (P <0.05). There was no difference between the other treatments and the control. The pattern of subterranean clover regeneration for the two herbicides was similar, but paraquat resulted in greater (P <0.01) subterranean clover regeneration than glyphosate.

Over all application times and years, forbs (mean 10 100 plants m$^{-2}$), other legumes (medics etc. mean 1540 plants m$^{-2}$), and other grasses (mean 1340 plants m$^{-2}$) were not affected by herbicide or grazing.

**2. Effect of herbicide rate** Herbicide application significantly (P <0.001) reduced

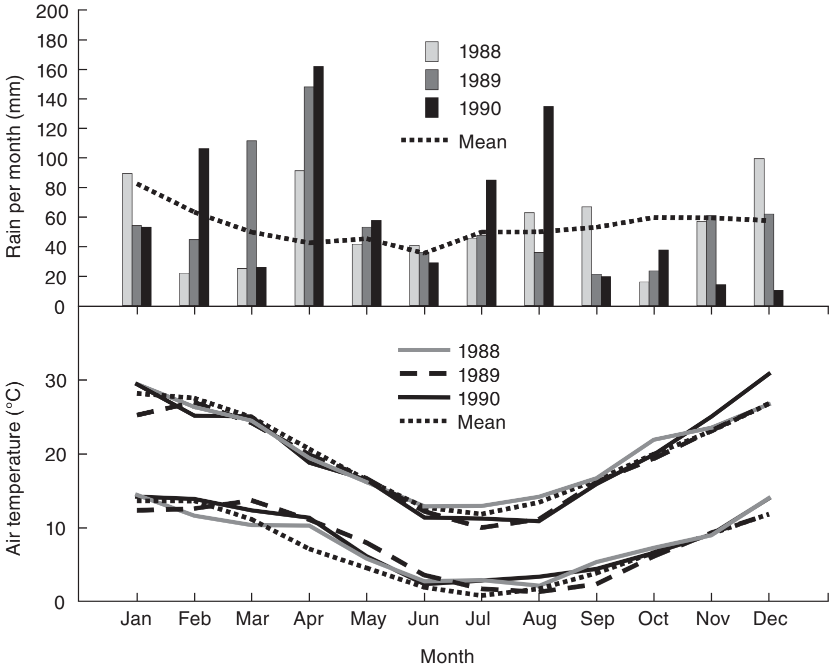


**Figure 1. Mean and monthly rainfall, and maximum and minimum air temperatures from 1988 to 1990. Data were derived from 'Datadrill' (Jeffrey *et al.* 2001). Average values are based on 30 years of data (1970–1999).**

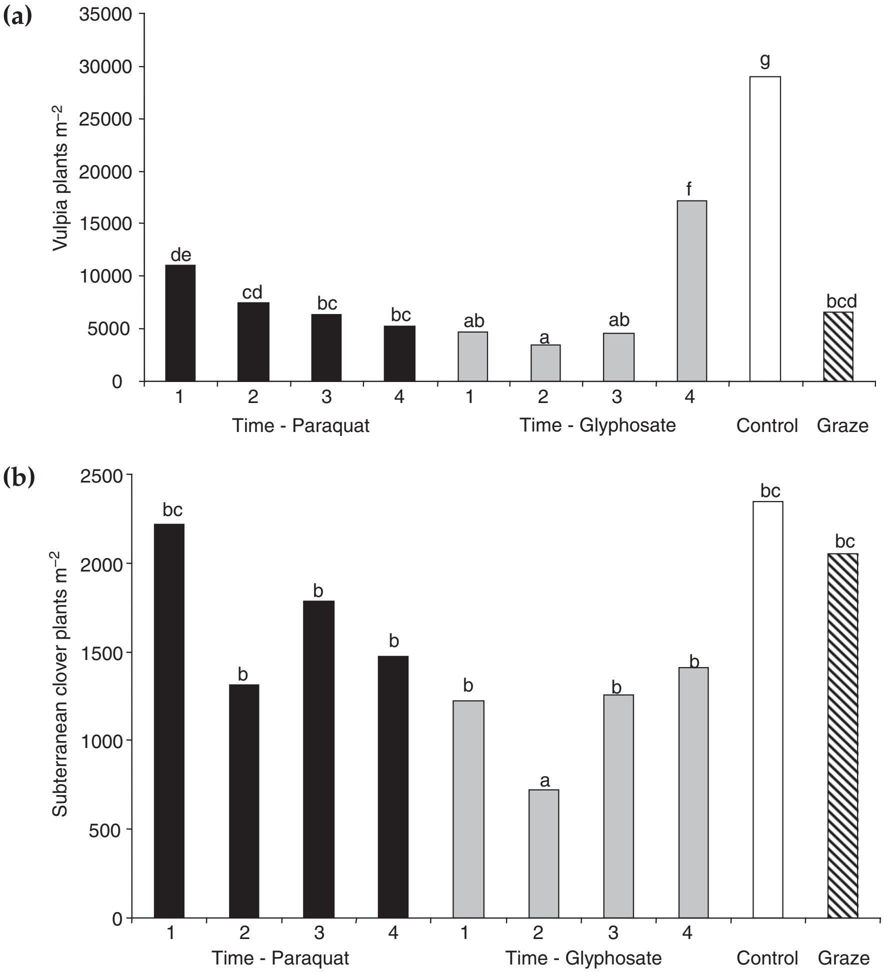


**Figure 2. Mean vulpia (a) and subterranean clover (b) regeneration after spraytopping at different times in spring with paraquat and glyphosate at recommended rates in 1988, 1989 and 1990. Times of application are listed in Table 1. Note: the grazed treatment was only applied in 1988. Columns with the same letters are not significantly different (P <0.001).**

vulpia and subterranean clover regeneration, with glyphosate having a significantly greater effect on subterranean clover than paraquat (Table 2). Doubling the herbicide rate reduced (P <0.001) vulpia regeneration compared to the recommended rate, but also severely affected subterranean clover regeneration, with the double glyphosate application rate significantly (P <0.05) reducing subterranean clover regeneration compared to the double paraquat rate. The herbicide × rate interaction for vulpia was not significant.

Forbs (mean 15 300 plants m$^{-2}$), other legumes (mean 2000 plants m$^{-2}$), and other grasses (mean 1460 plants m$^{-2}$) were not affected by herbicide nor herbicide rate.

**Table 2. The effect of herbicide (Nil, Glyphosate (Gly), and Paraquat (Par) applied in 1988), herbicide rate (Recommended (Rec) and 2X), and herbicide × rate interaction on seedling regeneration of vulpia and subterranean clover (plants m$^{-2}$). Level of significance indicated by < = P <0.05, and <<< = P <0.001.**

| Plant type | Herbicide | Rate | Herbicide * rate |
|---|---|---|---|
| Vulpia | Par, Gly<<<Nil | 2X<<<Rec | nsd |
| | 3680, 5010<<<24500 | 3190<<<5510 | |
| Subterranean clover | Gly<<<Par<<<Nil | 2X<<<Rec | 2XGly<2XPar, RecGly<RecPar |
| | 1040<<<1510<<<2400 | 1020<<<1530 | 690<1350, 1390<1670 |

**3. Repeat spraytopping applications** Spraytopping with both herbicides in 1988 resulted in lower (P <0.001) vulpia regeneration in the following year compared to the year 1 nil control (Figure 3). Spraytopping in two consecutive years with paraquat resulted in a similar level of regeneration as the initial application, whereas with glyphosate, the additional application further reduced vulpia regeneration compared to year 1 (P <0.001). When the herbicides were applied in year 1 only, vulpia regeneration after year 2 was similar to the control where no herbicide had been applied in years 1 and 2.

There was no significant effect of repeat application on subterranean clover (mean 1750 plants m$^{-2}$) and other legumes (mean 1300 plants m$^{-2}$). The trend for 'other' grasses (mean 710 plants m$^{-2}$) was similar to vulpia, with the nil herbicide treatment in year 2 resulting in higher plant numbers than the single spraytopping treatments (P <0.05). Year 2 seedling numbers of forbs were significantly (P <0.05) lower than for the initial year on both the nil (18 300 plants m$^{-2}$ vs. 6500 plants m$^{-2}$) and repeat herbicide treatments (18 900 plants m$^{-2}$ vs. 6600 plants m$^{-2}$).

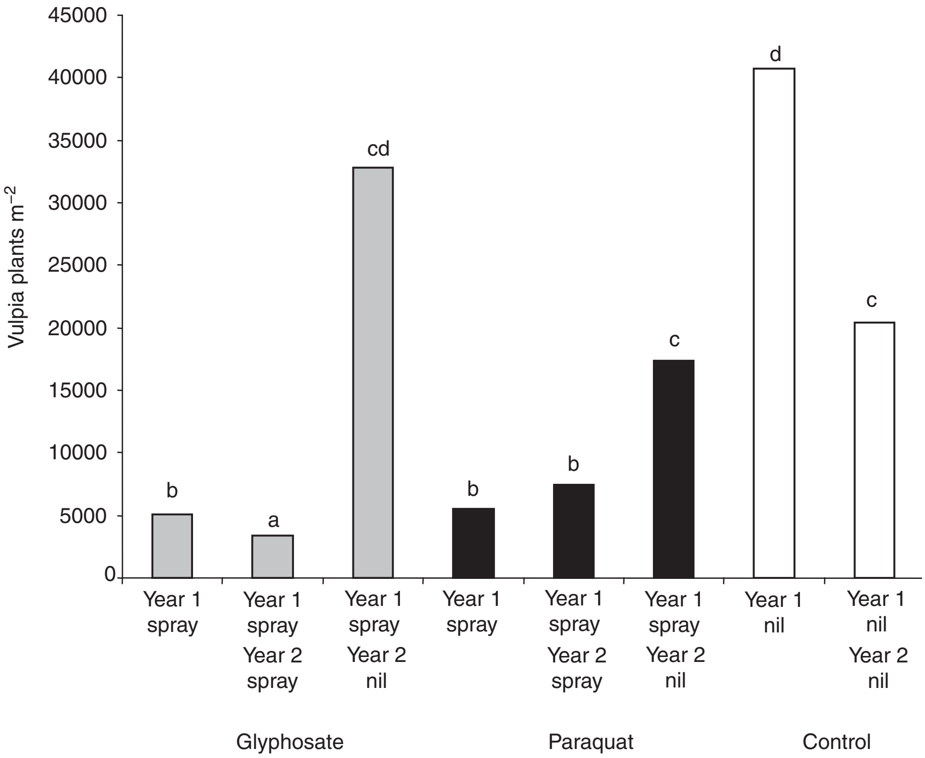


**Figure 3. Mean vulpia regeneration after spraytopping on one or two successive years in 1988, 1989 (year 1, year 2) with recommended rates of paraquat and glyphosate. Columns with the same letters are not significantly different (P <0.001).**

**4. Grazing vs. resting following spraytopping** Grazing reduced (P <0.01) vulpia regeneration compared to where there was no grazing (13 100 vs. 17 400 plants m$^{-2}$), while paraquat and glyphosate application also reduced (P <0.001) vulpia regeneration compared to the nil herbicide treatment (6560, 9800, 29 300 plants m$^{-2}$, respectively). There was no grazing × herbicide interaction, nor were subterranean clover or other species affected by either grazing or herbicide application.

## Discussion

Spraytopping with paraquat or glyphosate was shown to be an effective method for reducing seedling regeneration of vulpia, however timing of application needs to be optimized for maximum effect. In addition, collateral damage to other species in the pasture sward (especially subterranean clover) is an undesirable outcome that is also influenced by timing, and would need to be considered in any commercial spraytopping program (Wallace *et al*. 1998).

The greater effectiveness of later paraquat applications (80–95% peeping) and earlier glyphosate applications (65–85% peeping) confirms industry practice and supports the broad recommendations relating to optimum timing of herbicide application. The timing differential between the two herbicides is associated with their mode of action. The efficacy of paraquat, being non-translocated, is dependent on maximizing contact with reproductive plant material, so ensuring that a high proportion of the seedheads are green and visible above the flag leaf (peeping) will require a later application time than glyphosate. On the other hand, glyphosate needs to be translocated from the leaves to the reproductive structures to reduce seed viability, so seed-head appearance is not as critical for efficacy. The time taken for translocation (3–12 days depending on species – Caseley and Coupland 1985; three or so days for annuals – Anderson 1977), suggests that for vulpia, optimum application times for the two herbicides might be separated by 3–5 days. However, while the data indicate no differences between Times 2 and 4 for paraquat, and Times 1 and 3 for glyphosate over the three years of experimentation (Figure 2), lowest vulpia regeneration where paraquat and glyphosate were applied was at Times 4 and 2 respectively, a gap of 11, 7 and 5 days for 1988, 1989 and 1990 (Table 1). The longer time periods in the earlier years may be a reflection of less ideal field conditions for translocation.

The basis here for determining the optimum time for respective herbicide application is a physiological plant stage that changes rapidly during spring, and is easily defined and readily assessable by anyone who can count and perform a simple calculation. The two most frequently encountered species of vulpia in temperate Australia are *Vulpia bromoides* (L.) S.F.Gray and *V. myuros* (L.) C.C.Gmelin. Both these species commonly co-occur (McIntyre and Whalley 1990). For *Vulpia* spp., seedhead *appearance* (or peeping) can be measured over a scale of 0–100 and is a more appropriate measurement criterion than seedhead *emergence*, which for *V. myuros*, generally approaches, but seldom reaches 100% emergence through the flag leaf (Wheeler *et al.* 1990). The benefits of using a defined physiological stage accommodates the fact that seasonal conditions in each year are different, and pasture plants respond accordingly, providing a greater degree of commonality than a calendar date (Table 1.). Further, the semi-quantitative system proposed here provides a greater degree of precision in providing the appropriate timing for spraytopping than the arbitrary and impractical approach outlined in Dellow *et al.* (2003).

A similar rate of plant development was observed in 1988 and 1989, but a faster rate occurred in 1990, a year in which average maximum temperatures increased rapidly during spring (Figure 1b), particularly during the period of plant assessment. The more rapid development in 1990 was probably further enhanced by the drier soil resulting from below average rainfall received over spring in that year (McMaster 1997). The importance of temperature as the primary driver of plant development is shown in Figure 4 where per cent peeping is clearly influenced by cumulative daily mean temperature from 1 September ($R^2$ = 0.83). Importantly, it shows the effect of year where 90% peeping in 1988 and 1990 respectively required 675 and 530 degrees of cumulative daily temperature from 1 September, a difference of roughly two weeks. This is not surprising since temperature is probably the most significant factor affecting plant development (McMaster 2005).

Alternatively, cumulative mean temperatures (Figure 4) could be considered as a more direct primary guide for determining the timing optimum (assuming that such data is readily available), where 500 and 575 would be the values coinciding with optimum application times for glyphosate and paraquat, respectively (Figures 4, 5).

The greater effectiveness of herbicide on vulpia regeneration when applied at

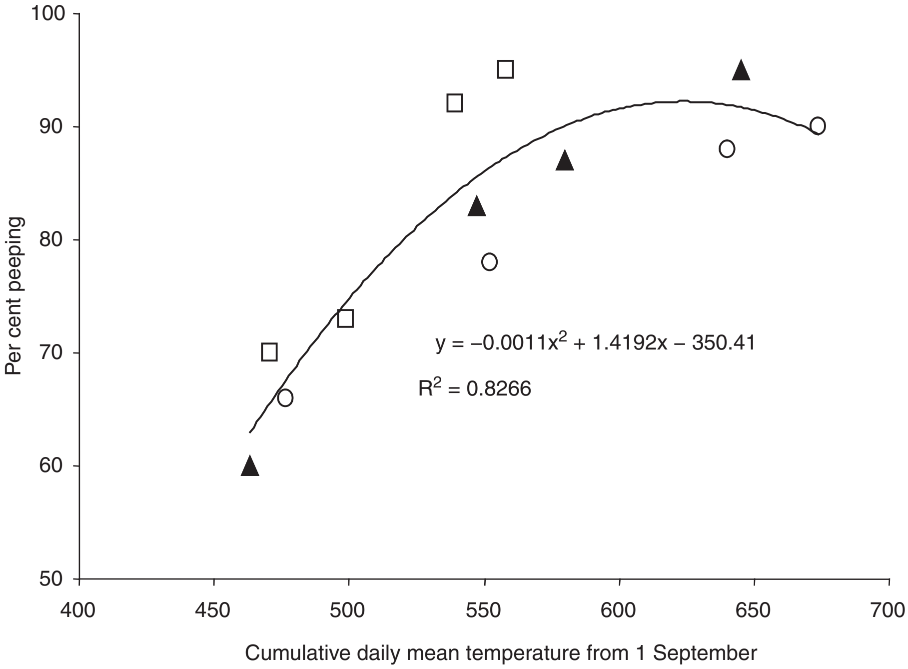


**Figure 4. Relationship between vulpia development (% peeping) and cumulative daily mean temperature from 1 September (Datadrill – Jeffrey *et al.* 2001) for each of the years 1988 (○), 1989 (▲) and 1990 (□).**

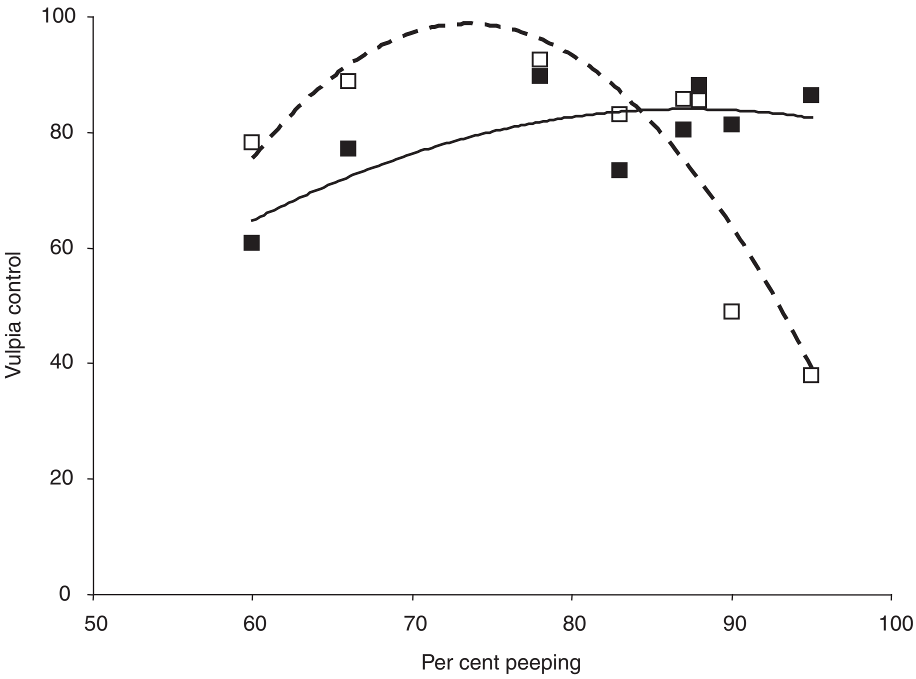


**Figure 5. Relative control of vulpia regeneration for optimum timing experiment in 1988 and 1989. Only three replicates shown for 1988, and two replicates for 1989 as they had a similar number of vulpia plants m$^{-2}$ (average 29 000). Open symbols represent glyphosate application, closed symbols represent paraquat application.**

**Equations for fitted curves:**
**Glyphosate:**
**Control = –0.1283*peeping$^2$ + 18.855*peeping – 593.75; $R^2$ = 0.8018.**
**Paraquat:**
**Control = –0.0259*peeping$^2$ + 4.5235*peeping – 113.39; $R^2$ = 0.5857.**

twice the recommended rate was expected, but the non-significant herbicide × rate interaction was not. The expectation was that the greater reliance of paraquat on extent of contact with plant tissue for efficacy would mean a greater degree of suppression than for glyphosate.

The reduction of vulpia regeneration by grazing around the time of seedhead appearance largely reflects the physical removal of the seedheads by grazing. Presumably, most of the defoliated material was ingested, the extent depending on feed quality characteristics and the grazing pressure applied. Seed viability after passage through the gut would be expected to be low (e.g. 1% viability for annual ryegrass – Gramshaw and Stern 1977). In addition, the viability of seeds contained in defoliated but discarded plant material would also be expected to be lower, depending on the proportion of immature/mature seeds present in the discarded plant material at the time of grazing. In commercial practice, however, the reduced regeneration from high stocking rates means high sheep numbers and/or relatively small paddocks (e.g. <10 ha) are required for success, and these circumstances would not be common in the Australian context.

The absence of a significant herbicide × grazing interaction is probably due to the glyphosate (applied at the same time as paraquat – 88% peeping) being less effective in reducing vulpia regeneration (17% vs. 40% for paraquat (Arnold and Barrett 1974) and 16% reduction where grazed). The optimum stage for glyphosate is 70–80% peeping (Figure 5).

All the seedling regeneration assessments reported here were based on soil cores collected in late summer and assessed over the next six months, about 9–10 months after the spraytopping treatments were applied. The practice for most spraytopping evaluations is to assess effectiveness some six months after herbicide application (Leys *et al.* 1991a,b). However, Figure 3 clearly shows that while spraytopping can substantially reduce vulpia regeneration (as assessed nine months later), if not followed up with a second herbicide application in the following spring, or preferably, some complementary management input imposed that increases the competitiveness of the other pasture species, then when assessed 18 months later after a natural seeding has been allowed to occur, vulpia plant numbers may be little different to the nil spraytopping treatment.

The mechanism for the rapid recovery of vulpia populations in a pasture that has been spraytopped appears to be associated with the rapid ecological growth rate of these species (Freckleton *et al.* 2000). A 6–9 month assessment might indicate that spraytopping has been effective in reducing vulpia plant numbers, but the population of other pasture species may also be reduced as a consequence. This would mean that the surviving vulpia plants might experience less competition and have more space to grow and develop, resulting in larger vulpia plants that produce 10–100 time more seed per plant than those present prior to spraytopping, and as a consequence, a greater density of vulpia plants when assessed after being allowed to seed, some 18 months after spraytopping. A similar outcome was evident following simazine application (Dowling *et al.* 2004). While reduced populations of other species were seldom evident in the experiments reported here, the low P status of the soil and the absence of P application (Dowling *et al.* 1997) probably was sufficient to still confer a competitive advantage on vulpia relative to the other species (Rossiter 1966).

It seems fairly clear that substantial reductions in vulpia field populations can be achieved by ensuring optimal timing of the spraytopping applications appropriate for the herbicide used, and grazing; and that further reductions can be obtained by increasing the herbicide application rate (unregistered rates), reapplying in successive springs, and perhaps grazing heavily following herbicide application.

An indication of the relative success of the treatments applied can be seen by expressing treatment seedling numbers as a proportion of the number of seedlings regenerating on the control treatments each year (Figure 5). Reductions appear to be high, ranging from 89% for grazing, through to 97% for optimal timing with recommended rates, to 98% at 2× the recommended rates. But more recent work by Freckleton *et al.* (2000) indicates that reductions in the order of 99% are required to ensure a progressive decline in vulpia populations. However, no matter what the applied treatments were, a substantial number of vulpia seedlings still remain, whether expressed on an absolute or relative basis. When these outcomes are coupled with seasonal (extended dry periods) and management (e.g. overgrazing) limitations, opportunities are created that provide space for vulpia populations to expand, with minimal competition from other pasture species. Under these circumstances, a dominant permanent presence of vulpia in temperate Australian pastures seems assured without an integrated approach to the problem.

## Conclusions

Spraytopping was shown to be an effective method for reducing vulpia populations in temperate pastures in Australia over the short-term. Control was significantly improved if respective herbicides were applied around the optimum time. The use of a highly discernible, easily recordable plant development stage (seedhead appearance – 'peeping') was proposed here as a more practical and accurate paddock based option for determining this time compared to the current procedures available. The use of cumulative mean temperatures might also have utility at a district level for determining these optimum times. Using heavier herbicide application rates, repeat applications and grazing, marginally improved the degree of control, however longer term control of vulpia in pastures will require associated pasture species to be more competitive.

## Acknowledgment

We wish to thank Mr Cam Ross for his cooperation and for making land available for the conduct of these studies.

## References

Anderson, W.P. (1977). 'Weed science: principles', 598 pp. (West Publishing Co, New York).

Arnold, G.W. and Barrett, D.W. (1974). The effect of paraquat desiccation in spring on plant and animal production from annual pastures. *Australian Journal of Experimental Agriculture* 14**,** 23-32.

Caseley, J.C. and Coupland, D. (1985). Environmental and plant factors affecting glyphosate uptake, movement and activity. *In* 'The herbicide glyphosate', eds E. Grossbard and D. Atkinson, pp. 92-123. (Butterworths, London, UK).

Dellow, J.J., Scott, M.C. and Pengilley, K.R. (2003). Weed control in lucerne and pastures 2004. NSW Agriculture, 64 pp.

Dellow, J.J., Wilson, G.C., King, W.M. and Auld, B.A. (2002). Occurrence of weeds in the perennial pasture zone of New South Wales. *Plant Protection Quarterly* 17**,** 12-16.

Dowling, P.M., Leys, A.R. and Plater, B. (1997). Effect of herbicide and application of superphosphate and subterranean clover seed on regeneration of vulpia in pastures. *Australian Journal of Experimental Agriculture* 37, 431-8.

Dowling, P.M., Leys, A.R., Verbeek, B., Millar, G.D., Lemerle, D. and Nicol, H.I. (2004). Effect of annual pasture composition, plant density, soil fertility and drought on vulpia (*Vulpia bromoides* (L.) S.F.Gray). *Australian Journal of Agricultural Research* 55, 1097-1107.

Freckleton, R.P., Watkinson, A.R., Dowling, P.M. and Leys, A.R. (2000). Determinants of the abundance of invasive annual weeds: community structure and non-equilibrium dynamics. *Proceedings of the Royal Society of London. Series B Biological Sciences* 267, 1153-61.

GenStat (2000). 'GenStat 5 for Windows, Release 4.2.' (Lawes Agricultural Trust, Rothamstead Experimental Station, UK).

Gramshaw, D. and Stern, W.R. (1977). Survival of annual ryegrass in a Mediterranean environment. *Australian Journal of Agricultural Research* 28, 81-91.

Jeffrey, S.J., Carter, J.O., Moodie, K.B. and Beswick, A.R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climatic data. *Environmental Modelling and Software* 16, 309-30.

Kemp, D.R. and Dowling, P.M. (1991). Species distribution within improved pastures over central NSW in relation to rainfall and altitude. *Australian Journal of Agricultural Research* 42, 647-59.

Leys, A.R., Cullis, B.R. and Plater, B. (1991a). Effect of spraytopping applications of paraquat and glyphosate on the nutritive value and regeneration of vulpia (*Vulpia bromoides* (L.) S.F.Gray). *Australian Journal of Agricultural Research* 42, 1405-15.

Leys, A.R., Plater, B. and Cullis, B. (1988). Response of six temperate annual grass weeds to six selective herbicides. *Plant Protection Quarterly* 3, 163-8.

Leys, A.R., Plater, B. and Lill, W.J. (1991b). Response of vulpia (*Vulpia bromoides* (L.) S.F.Gray and *V. myuros* (L.) C.C.Gmelin) and subterranean clover to rate and time of application of simazine. *Australian Journal of Experimental Agriculture* 31, 785-91.

McIntyre, S. and Whalley, R.D.B. (1990). Co-occurrence of *Vulpia* species on the northern tablelands of New South Wales. *Australian Journal of Botany* 38, 445-50.

McMaster, G.S. (1997). Phenology, development, and growth of the wheat (*Triticum aestivum* L.) shoot apex: a review. *Advances in Agronomy* 59, 63-118.

McMaster, G.S. (2005). Centenary review: phytomers, phyllochrons, phenology and temperate cereal development. *Journal of Agricultural Science, Cambridge* 143, 137-50.

Michalk, D.L., Dowling, P.M., Kemp, D.R., King, W.McG., Packer, I.J., Holst, P.J., Jones, R.E., Priest, S.M., Millar, G.D., Brisbane, S. and Stanley, D.F. (2003). Sustainable grazing systems for the Central Tablelands, New South Wales. *Australian Journal of Experimental Agriculture* 43, 861-74.

Moore, R.M. (1970). South-eastern temperate woodlands and grasslands. *In* 'Australian grasslands', ed. R.M. Moore, pp. 169-90. (ANU Press, Canberra).

Quigley, P.E., Ward, G.N. and Morgan, T. (1992). Botanical composition of pasture in south-western Victoria. Proceedings of the 6th Australian Agronomy Conference, eds. K.J. Hutchinson and P.J. Vickery, pp. 533. (Australian Society of Agronomy, Armidale, NSW).

Rossiter, R.C. (1966). Ecology of the Mediterranean annual-type pasture. *Advances in Agronomy* 18, 1-56.

Wallace, A., Lancaster, R.A. and Hill, N.L. (1998). Application of non-selective herbicides during flowering of pasture legumes can reduce seed yield and alter seed characteristics. *Australian Journal of Experimental Agriculture* 38, 583-94.

Wheeler, D.J.B., Jacobs, S.W.L. and Norton, B.E. (1990). Grasses of New South Wales. (University of New England Publishing Unit, Armidale).

Zadoks, J.C., Chang, T.T. and Konzak, C.F. (1974). A decimal code for the growth stages of cereals. *Weed Research* 14, 415-21.