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Integrated Management Strategies for the Control of Serrated Tussock in Inaccessible Native Pastures

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Abstract

Serrated tussock is an unpalatable perennial grass weed that invades temperate pastures of south-eastern Australia. Management of this weed is particularly problematic in native pastures due to them being commonly located on steep and/or rocky ground that cannot be accessed by machinery, or on infertile soils that cannot economically sustain introduced pasture species. This project examined the success of different combinations of management strategies (grazing, herbicide and oversowing) to manage serrated tussock on upper and lower slopes of infertile country with native pastures. It examined interactions between serrated tussock and native grasses and tested several novel techniques to weaken the vigour of serrated tussock. The first step in dealing with this devastating weed is to minimise disturbance *i.e.* decreasing opportunities for serrated tussock seedlings to establish and increasing the competitiveness of existing perennial native grasses, then use herbicides as often as required to kill any serrated tussock plants while minimising disturbance and the bare ground where weed species can establish. Maintaining at least 1.5 t DM ha^{-1} herbage mass of desirable native perennial grasses at all times of the year is particularly critical to prevent serrated tussock seedlings surviving. On upper slopes the dominant native species are often *Austrodanthonia* spp., which are not often considered competitive, but they did successfully limit the spread of serrated tussock when managed appropriately. On lower slopes *Microlaena stipoides* is a more aggressive competitor, but does needs to be encouraged to spread and limit any further invasion by serrated tussock, and when adult serrated tussock plants are killed to then occupy the space created. Oversowing with competitive species was not successful, due to dry seasons. Novel practices to help control serrated tussock; gibberellic acid to try and increase digestibilities, silicon to modify the plant's physiology and Thatchbusta® to breakdown litter, were tried but with no benefits. Evidence of allelopathic effects of fresh serrated tussock leaves and roots on germination of grass seeds was found, though litter had limited positive effect on plant growth. Those results suggest that serrated tussock has no additional mechanisms to discourage recruitment of desirable plants other than competition for resources. The results from this project provide farmers with information on how to better manage their native pastures to maximise production and reduce the current and future costs of serrated tussock. Extension materials developed by the project guide farmers to the most appropriate control techniques to use and enable them to estimate the effects of potential control techniques on their net returns.

Executive Summary

Background

Serrated tussock (*Nassella trichotoma*) is an unpalatable perennial grass weed, from South America, that invades temperate pastures in higher rainfall areas (>500mm) in south-eastern Australia as well as similar environments in New Zealand and South Africa. Control of serrated tussock in native pastures is difficult as they are often located on steep and/or rocky ground with poor soils that make conventional control methods impractical. The main option now available to livestock producers is to manage the native grass infested areas in ways that enhance the competitiveness of existing desirable species. Understanding ways of strengthening native pastures against this disastrous weed is the thrust of this report.

Aims and objectives

Control of *N. trichotoma* in native pastures is currently achieved by many producers, by regular applications of the herbicide flupropionate (every 2-4 years). This control method is expensive and often leads to mortality of useful perennial grass species. The aim of this project was to find alternatives to this control practice by investigating which combinations of grazing management, herbicide use and broadcast sowing of pasture species, used in an appropriate sequence, provided the best serrated tussock management through a reduction in serrated tussock seedling establishment and reducing the adult serrated tussock plant herbage mass. Treatments were compared at a paddock scale on upper and lower slopes where geological processes produce soils with differing nutrient and moisture conditions resulting in different botanical composition and plant competitiveness. Conditions on upper and lower slopes represented the range of environments where this weed occurs. The project examined competitive and chemical interactions between serrated tussock and native grasses, and several novel techniques to weaken the vigour of serrated tussock.

Project findings

Key results from this project are:

- Minimising any disturbance that creates niches for seedling recruitment of serrated tussock and which reduces competition from desirable perennial grasses, is the primary requirement for preventing invasion by serrated tussock.
- A new analytical tool was developed to identify the likelihood of success or failure of management practices based on the need to achieve both the herbage mass of desirable perennial grasses above a threshold and for the biomass ratio of desirable perennial grasses (PG) : serrated tussock (ST) to be at least 5.
- On upper slopes, active grazing tactics (rests to maintain >1.5 t DM ha^{-1}) and the application of herbicide in ways (*e.g.* spot spraying with flupropionate) that minimise disturbance resulted in the more competitive pastures.

- On the lower slopes, maximum pasture competitiveness was achieved in ungrazed paddocks and paddocks that were actively grazed (rests to maintain >1.5 t DM ha^{-1}) where serrated tussock was spot sprayed with flupropionate.
- Oversowing with competitive pasture species did not work in these dry years as few plants established. The existing sward produced sufficient competition to limit any recruitment of serrated tussock seedlings.
- Serrated tussock contains allelopathic chemicals that have small effects on the growth of perennial native grasses, though this effect seemed confined to fresh plant material and not the litter.
- Measurements of photosynthetic rates found that serrated tussock had higher rates than *Microlaena stipoides*. This indicated that serrated tussock may have greater reserves to recover from stress than the native grass.
- *Microlaena stipoides,* found typically on lower slopes, was a more aggressive competitor for serrated tussock than *Austrodanthonia* spp. common on upper slopes, though the later still exerted a useful level of competition in the paddock over summer. Defoliation significantly reduced the competitive ability of the native grasses.
- Upper and lower slopes responded differently to treatments and practices do need to be adjusted for local variation in pasture components and competitiveness.
- Decision support tools were developed for producers who have some difficulty in resolving the better strategies and tactics to halt the spread of and then reduce serrated tussock.
- Applying glyphosate when desirable perennial C3 grasses are dormant was a successful strategy for reducing serrated tussock herbage mass on upper slopes while having minimal impacts on these useful perennial grasses.

Conclusions and recommendations

Serrated tussock can be controlled, but it takes 3D's: diligence, deliberation and (minimal) disturbance. A sequence for better management of serrated tussock has been developed from the results of this project, plus prior knowledge and projects run by the team that utilises these 3D's. They are as follows:

1. Use the decision support tool (*Serrated tussock: Getting the basics right*) developed in this project to determine the most appropriate control scenario. (The likely more common pathway is sequenced below.)
2. Use the economic model (*Serrated tussock: Estimating benefits of control in native and natural pastures*) to examine the economic benefits of a control scenario.
3. Select the initial paddocks for change (those with low to medium overall densities of serrated tussock and >30% desirable perennial grasses).
4. Manage pastures using the following rules;

   a. Rule 1 - Retain greater than 1.5 t ha^{-1} of perennial grass herbage mass at all times of the year to ensure adequate competition against serrated tussock seedlings.
   b. Rule 2 - Maintain a ratio of perennial grass : serrated tussock of greater than 5:1 to provide competition against adult serrated tussock plants.
   c. Rule 3 - Follow guidelines developed by the pasture recruitment project (MLA PAST.125) to ensure perennial grasses recruit. Those recommendations are not in conflict with the better management practices recommended here.

5. Apply herbicides to the rested paddock. The rules for herbicide use (below) can alleviate negative impacts of herbicides on desirable species and assist in the maintenance of herbage mass and the 5:1 ratio of perennial grass : serrated tussock herbage mass.
   a. Rule 4 - If a pasture is dominated by C4 grasses, apply broadacre glyphosate in winter, and spot spray surviving plants with flupropoanate.
   b. Rule 5 - If a pasture is dominated by C3 species, apply broadacre glyphosate in summer, and spot spray surviving plants with flupropoanate.
   c. Rule 6 - If a pasture is dominated by any grass other than red grass (*Bothriochloa macra*) or kangaroo grass (*Themeda australis*) and broadacre flupropoanate is applied then the paddock must remain ungrazed until adequate perennial grass herbage mass (see rules a and b of grazing management) is present.
6. The paddock can be grazed from late autumn until early the next summer, but aim to maintain the herbage mass of desirable perennial grasses >1.5 t DM ha^{-1} at all times of the year. If paddocks are grazed below this level with the intention of allowing herbage mass to return but drought occurs then paddocks will be highly susceptible to further invasion.

7. Repeat this cycle of management every year to reduce the density of the serrated tussock infestation. It is important to maintain a herbage mass >1.5 t DM ha^{-1} at al times of the year so that the risk of re-invasion is minimised. Over time there will be a build-up in herbage mass, litter and fertility which can then be utilised with more livestock.

The weed is not the sole focus of a serrated tussock management program; pasture and animal health are of equal importance. Stock type and management need to be considered and this may be relatively simple changes such as reducing mob numbers by combining mobs, or fencing areas off to create more paddocks, to more complex changes such as changing an enterprise from fine wool to fat lambs.

Contents

1 Background

Serrated tussock (*Nassella trichotoma*) is an unpalatable perennial grass weed from South America, that invades temperate pastures in higher rainfall areas (>500mm) of south-eastern Australia as well as similar environments in New Zealand and South Africa. The weed costs $40 million in production penalties in NSW alone. Control of serrated tussock in native pastures is difficult as it is often located on steep and/or rocky ground with poor soils that make more conventional control methods impractical. The costs of replacing serrated tussock with competitive introduced perennial grasses are much greater than returns from livestock can afford, except on the higher rainfall, more fertile soils. Seed of native grasses is rarely available commercially and currently very expensive if it is, nullifying its use in a replacement, resowing philosophy.

Previous research and development has provided much valuable information on how integrated strategies for control of serrated tussock seedlings in native pastures can be developed. This is the first step in restricting the spread of this weed. The assessment of these strategies on a larger scale is yet to be done and the suitability of these strategies for various parts of the landscape (*e.g.* upper and lower slopes) where soil properties and pasture composition differ is also unknown. Control of adult plants is though more problematic. Research is required on alternative methods of controlling adult serrated tussock plants that maintain production and keep control costs low. The primary option available to livestock producers is to manage the native grass infested areas in ways that enhance the competitiveness of existing desirable species and then within that framework identify workable solutions for controlling the weed. Understanding ways of strengthening native pastures against this disastrous weed and then intervening in practical ways to control adult plants is the thrust of this report.

2 Project Objectives

The objectives of this project were to deliver control strategies that enabled producers to potentially double stocking rates in currently infested areas (carrying 1-2 DSE $ha.yr^{-1}$) for an industry wide gain of *c*. $20m per annum. Larger gains may be possible and the weed management strategies developed will have application in wider weed management contexts.

The project was designed to:

- develop management practices to significantly limit the recruitment of serrated tussock seedlings within serrated tussock infested native grasslands.
- develop rules for managing serrated tussock infested grasslands for upper and mid-lower slope communities where the native perennial grass species and site productivity differs.
- determine the efficacy of novel management methods based on manipulating herbage mass, litter and soil nutrient levels to reduce the competitiveness of adult serrated tussock plants.

- develop operational links with the Serrated Tussock Taskforce.
- publish extension material on recommendations on outcomes from the project and holding at least four field days for producers and advisors to demonstrate control principles.

This project focused on developing cost-effective management strategies to:

- strengthen useful grasses within existing grasslands to limit invasion by serrated tussock,
- reduce annual control costs, and
- reduce the area of dense infestations to limit weed spread.

Emphasis was in lower rainfall, lower fertility areas where the economics of sowing competitive pastures are dubious and where regular herbicide use (often every 3-4 years) is the only current method of control; herbicides often damage useful perennial pasture species and the risk of herbicide resistance is increasing.

This project formed a part of a wider serrated tussock research program with projects funded by the Defeating the Weeds Menace program, Australia Wool Innovations and the Rural Management Research Institute that focussed on the social aspects of serrated tussock control in native pastures. Results from the wider research program have been considered when developing the extension materials produced by this project.

3 Methods

3.1 Enhancing pasture competitiveness

A series of field, laboratory and glasshouse experiments were done to investigate ways of influencing the competitiveness between serrated tussock and native perennial grasses.

3.1.1 Trunkey Creek field experiment on upper and lower slopes

Native pastures on upper and lower slopes were used to reflect the different growing environments where this weed is found. Upper slopes are generally characterised by shallow soils with poor fertility and water holding availability. This is because most of the soil has moved down the slope where it has accumulated. This results in deeper soils on the lower slopes, relative to the upper slopes, that have improved soil fertility and moisture holding abilities, and subsequent differences in botanical composition and plant competitiveness.

The primary study for the project was a large field experiment established at Trunkey Creek on the NSW Central Tablelands in 2006. This experiment investigated management strategies designed to maximise the competitiveness of native perennial grasses in serrated tussock invaded native pastures to first prevent seedling recruitment of serrated tussock and then exert pressure on and reduce the density of mature plants to limit their ability to grow, set seed and increase the level of infestation. Part of these objectives included the goal of increasing the productivity of native grasses. This large experiment used a factorial combination of:

1. grazing (3 treatments); constantly grazed by the farmer at their standard stocking rates, actively grazed *i.e.* only grazed down to 1.5 t DM ha^{-1} when biomass of desirable perennial grasses reached >2 t ha^{-1}, and ungrazed,

2. herbicide (3 treatments); nil, broadacre sprayed glyphosate when desirable perennial grasses were not growing in summer, and spot sprayed with flupropionate,

3. oversowing (3 treatments); nil, native grass species seed added or a ryegrass / subterranean clover / fertiliser treatment based on current local recommendations, designed to provide quick competitive growth for serrated tussock seedlings, and

4. serrated tussock density (3 treatments); low, medium or high.

All 81 combinations of these factors were replicated twice on both upper and lower slopes of a moderately infested paddock (324 plots). Pasture composition and biomass were estimated each season using BOTANAL procedures (a rapid non-destructive method of sampling grassland species composition and structure of plant functional groups, herbage mass – green and total, ground cover, bare ground and litter) for 27 times for each treatment combination, ~3,000 quadrats per sampling period. Main effects of grazing, herbicide and oversowing treatments on upper and lower slopes were analysed using REML procedures to account for spatial variation and the success of treatment combinations was assessed using a pasture matrix developed by the project.

3.1.2 Ecosystem effects on serrated tussock seedling recruitment

The effect of grassland state and condition on seedling recruitment of serrated tussock was studied at the main field experiment in an overlay of that experiment. The treatments imposed (Section 3.1) were used to generate variation in plant species composition, plant functional groups, total and green herbage mass, bare ground, litter and ground cover. Serrated tussock seedlings were counted at the same time BOTANAL measurements were taken. Seedling densities were counted from winter 2006 to autumn 2008 at approximately three-month intervals. Those surviving each summer (the critical period for seedling survival) were then analysed in relation to the factors measured by BOTANAL using a regression tree, which directly provides threshold values for decision making.

3.1.3 Effect of defoliation on competition between serrated tussock and native grasses

A glasshouse experiment was done to examine whether defoliation (to simulate grazing) of competing native grasses, *Microlaena stipoides* and *Austrodanthonia linkii*, provided a competitive advantage to establishing serrated tussock seedlings and how any competitive advantage was influenced by soil fertility. A single serrated tussock seedling was planted in the centre of pot that contained up to eight plants of the competing species. Differences in biomass between treatments at the conclusion of the experiment were used to determine the effect of defoliation and soil fertility on competition.

3.1.4 Is allelopathy involved?

Laboratory and glasshouse experiments were done to determine whether the presence of serrated tussock roots and leaves affected the germination and growth of two native grass species, *Microlaena stipoides* and *Themeda australis.* The laboratory experiment investigated the effect of teas made from the leaves or roots of serrated tussock plants on the germination of seeds of native grass species. Serrated tussock plant material was harvested fresh and dried at room temperature. The glasshouse experiment investigated the effect of different levels of serrated tussock leaf litter on the soil surface on the growth of seedlings of the native grasses. The amount of litter replicated that found in low, moderate and high density infestations.

3.2 Novel control methods

Ideally farmers would like to apply a treatment or control method that could weaken serrated tussock plants and reverse the invasive process. Herbicides are used for this purpose and were major treatments in the main field studies as well as grazing and over-sowing practices. In addition a series of other studies were done to investigate the efficacy of novel methods about which there had been reasonable arguments that they could have an impact. These studies were designed to provide further insight into the strengths and weaknesses of serrated tussock.

3.2.1 Gibberellic acid

A primary effect of the plant hormone Gibberellic acid (GA) is to cause etiolation (*i.e.* long weak stems and longer, softer and less dense leaves). It was hypothesised that the application of GA could alter the palatability and quality of serrated tussock plants making them more susceptible to grazing pressure. A glasshouse experiment was done to determine whether the application of GA affected the quality and palatability of serrated tussock and two native grasses, *Microlaena stipoides* (C3) and *Chloris truncata* (C4). GA is readily available and could be applied using equipment already owned by many farmers. *C. truncata* was used as seed of *T. australis*, a common larger tussock native grass, was not available.

3.2.2 Thatchbusta®

Thatchbusta® is a propriety product that claims to break down high density areas of thatched roots and increase clover production through improved soil biological activity. A commercial trial of this product was established on 220 ha at Hill End on the NSW Central Tablelands. This field trial tested whether the use of Thatchbusta® would increase the rate of recovery of useful grass species within a paddock treated with broadacre flupropionate. Plots were either unsprayed, broadacre sprayed with flupropionate at the recommended rate, spot sprayed with flupropionate or aerially sprayed with a mixture of flupropionate, lime, reactive rock phosphate and Thatchbusta®. Seasonal BOTANAL sampling was done to estimate pasture biomass, species composition, percentage green biomass and bare ground from autumn 2006 to summer 2007.

3.2.3 Silicon

Previous research has demonstrated that the application of silicon (Si) alters a plant's water use efficiency and photosynthetic activity (Hattori *et al.* 2008; Nwugo and Huerta 2008). It was hypothesised that applying silicon could influence these physiological parameters and affect competitive interactions between serrated tussock and native grasses by reducing the competitiveness of serrated tussock. A glasshouse experiment was done to determine whether the application of silicon to the plant growth medium affected the photosynthetic activity and competitive interactions of serrated tussock and a native perennial grass, *Microlaena stipoides* under well-watered and water stressed conditions. Silicon comes in many forms so can be applied using equipment that many farmers would already own (*e.g.* fertiliser spreader, boomspray) and, because it is one of the more common elements on earth, it is relatively inexpensive.

4 Results and Discussion

The main results from the suite of experiments done are summarised here. These are the main effects from which better recommendations have now been derived for the improved control of serrated tussock. More complete details will be published in journal papers to come from this project.

4.1 Managing pastures

4.1.1 Trunkey Creek field experiment management sequence

The grazing treatments were first applied in mid-2006 and continued for the entire duration of the experiment, herbicide treatments commenced in late-2006 and the oversowing treatment started in mid-2007. The reasoning behind this order of treatments was to begin grazing management first so that perennial grass herbage mass could accumulate and provide competition against serrated tussock and that the application of herbicide would be done prior to the oversowing. This was so herbicides would open up resource gaps in which the sown seed could germinate and establish. This sequencing is based upon local research (Sustainable Grazing Systems experiment at Carcoar) showing that getting the sequence right can be as, or more important than, some individual treatment effects.

The experience gained during this project supported this view for a sequential approach. Though the drought years that dominated during the course of this project meant that rates of change were initially very slow and most of the important effects only started to emerge in the final year. Only one herbicide application was made to each treatment as the aim was to clearly establish the effects of each factor. The efficacy of a single herbicide treatment was in turn affected by the dry seasons. Spot spraying is often done annually and in practice would likely result in a faster set of outcomes and pasture improvement than found in this project.

Both the grazing and herbicide treatments identified practices that did reduce the infestation of serrated tussock and were particularly important in preventing seedling recruitment of this weed. Over-sowing treatments were not successful as few plants established during the dry seasons. The results on oversowing are not presented here. The other treatments did though show how existing species could provide sufficient competition to help control serrated tussock. The results presented here will first discuss individual effects and then how treatments interacted to give better results from combining tactics.

4.1.1.1 Stocking rates

The actively grazed treatment used rules based upon herbage mass to decide when to rest and when to graze the pasture, through the warmer six months of the year. These plots were initially ungrazed for some time to enable the herbage mass to reach ~2 t DM ha^{-1}. Due to the drought no grazing then occurred on the actively grazed treatment in 2006 and 2007 (Table 1). The numbers of animals and days of grazing were recorded on the actively grazed and constantly grazed plots and the mean annual stocking rate calculated. In 2008 and 2009, which were still drier years than average, the actively grazed treatment had an average stocking rate of 1.7 DSE ha^{-1}, ~75% that of the 2.3 DSE ha^{-1} in constantly grazed. These values are typical of the upper range expected on the natural pasture communities of the NSW Tablelands (Vere and Kemp, *unpublished data*). It is estimated that in 1950 these grasslands were stocked at 3 DSE ha^{-1}, but today many areas are around 1 DSE ha^{-1}, illustrating the decline in productivity that has occurred, in part due to the invasion by serrated tussock.

Table 1 Stocking rates (DSE/ha/annum) for actively grazed and constantly grazed treatments for upper and lower slopes of the Trunkey Creek field site.

Year	Slope	Stocking rate (DSE/ha/annum)	
		Actively grazed	**Constantly grazed**
2006	Upper	0	2.9
	Lower	0	1.8
2007	Upper	0	2.9
	Lower	0	1.8
2008	Upper	1.0	2.8
	Lower	2.6	1.8
2009	Upper	1.4	2.8
	Lower	1.7	1.8

4.1.1.2 Effects of herbicide and grazing management

The general treatment effects are presented in this section and then a new methodology is presented that enables a better analysis of the interactions between treatments.

Analyses by REML procedures indicated that perennial grass herbage mass, serrated tussock herbage mass and the perennial grass : serrated tussock herbage mass ratio differed between slope positions ($P < 0.001$, $P < 0.001$ and $P = 0.031$, respectively; data not shown). This meant that analysis of herbicides and grazing were analysed separately for upper and lower slopes.

Serrated tussock herbage mass

The dry seasons resulted in the average herbage mass, total and for individual species, remaining low for the first two years of this study. Only in 2008 with higher rainfall, did herbage mass increase substantially, which then enabled treatment differences to be more readily discerned.

Serrated tussock herbage mass was greater in the ungrazed treatment for the upper slopes (Figure 1) and constantly grazed and ungrazed treatments for the lower slopes (Figure 2). The season x grazing treatment interaction for serrated tussock herbage mass was significant for the upper and lower slopes ($P < 0.001$). These are average effects across treatments.

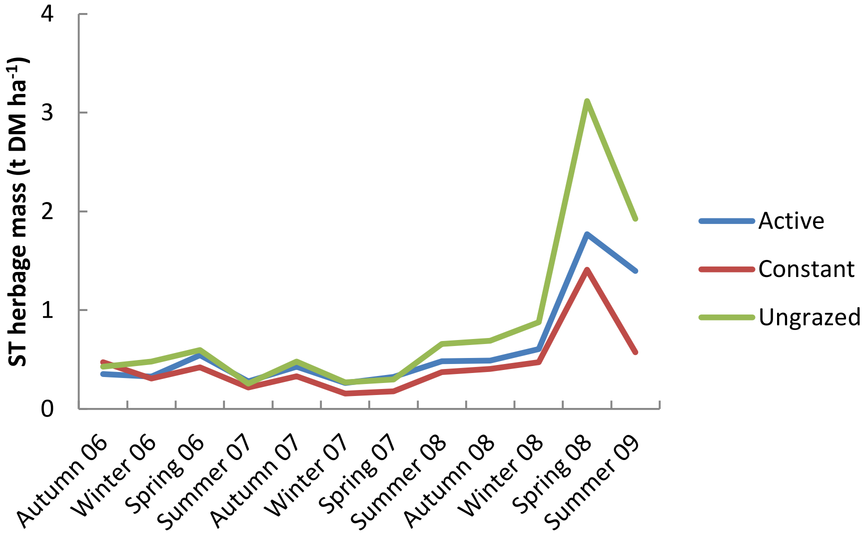


Figure 1 Serrated tussock herbage mass for active, constant and ungrazed treatments on the upper slopes of the Trunkey Creek field site for the duration of the experiment.

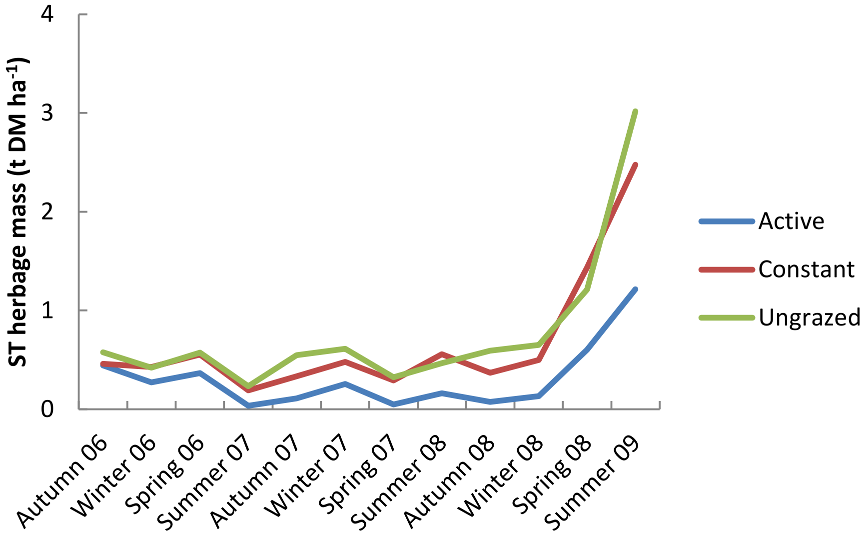


Figure 2 Serrated tussock herbage mass for active, constant and ungrazed treatments on the lower slopes of the Trunkey Creek field site for the duration of the experiment.

Results show that for upper and lower slopes, plots sprayed with flupropanate had the lowest serrated tussock herbage mass and that glyphosate treated plots had a lower serrated tussock herbage mass than the nil herbicide treatment. The season x herbicide treatment interaction for serrated tussock herbage mass was significant on the upper ($P < 0.001$; Figure 3) and lower slopes ($P < 0.001$; Figure 4).

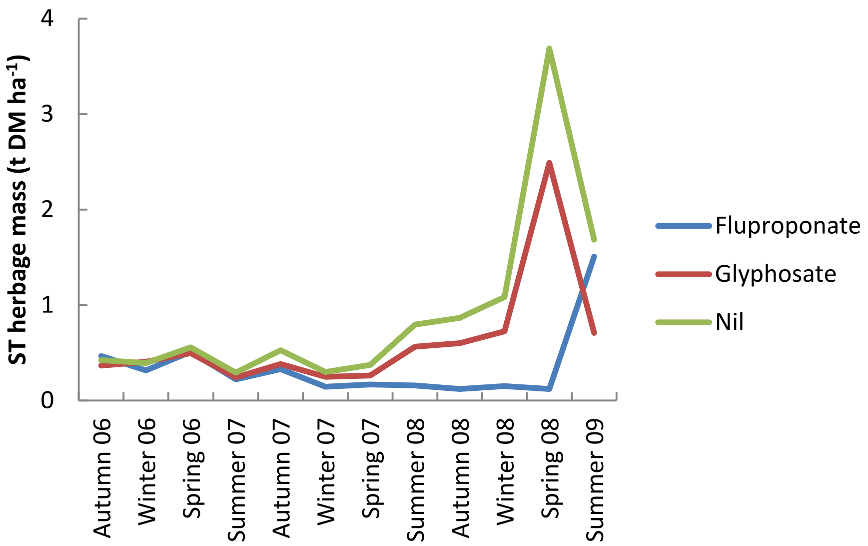


Figure 3 Serrated tussock herbage mass for spot sprayed fluproponate, broadacre glyphosate and nil herbicide treatments on the upper slopes of the Trunkey Creek field site for the duration of the experiment.

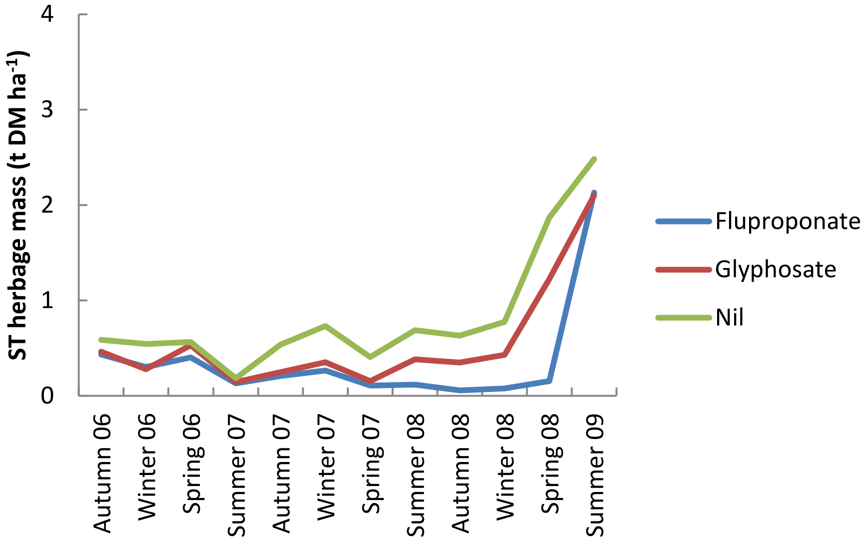


Figure 4 Serrated tussock herbage mass for spot sprayed flupropionate, broadacre glyphosate and nil herbicide treatments on the lower slopes of the Trunkey Creek field site for the duration of the experiment.

Perennial grass herbage mass

The goal of a serrated tussock management program is not only to remove serrated tussock but to also ensure that perennial grasses remain to outcompete any serrated tussock seedlings. The season x perennial grass herbage mass interaction was significant for grazing and herbicide treatments on both upper and lower slopes. On upper slopes, the perennial grass herbage mass of the constantly grazed treatment was significantly lower than both the active and ungrazed treatments ($P < 0.001$; Figure 5). On lower slopes however, the perennial grass content of active and constantly grazed treatments were significantly less than the ungrazed treatment ($P < 0.001$; Figure 6).

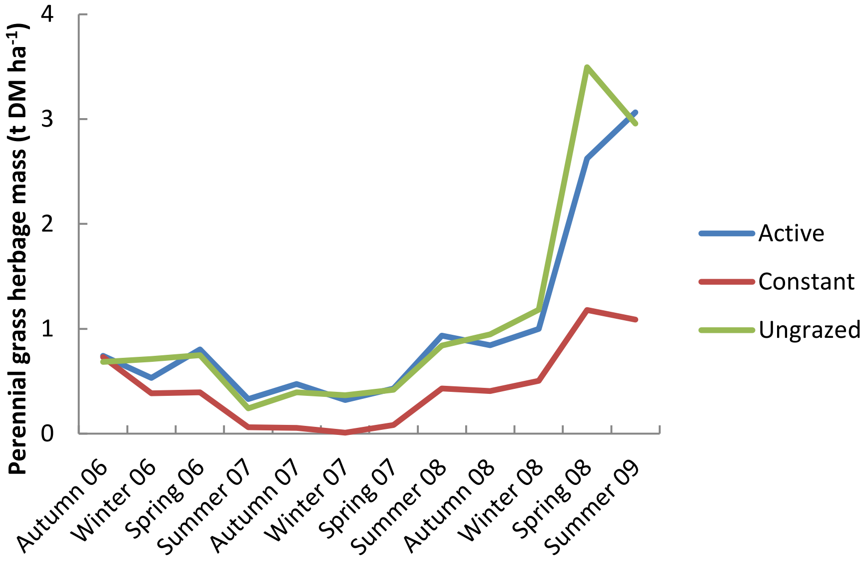


Figure 5 Perennial grass herbage mass for active, constant and ungrazed treatments on the upper slopes of the Trunkey Creek field site for the duration of the experiment.

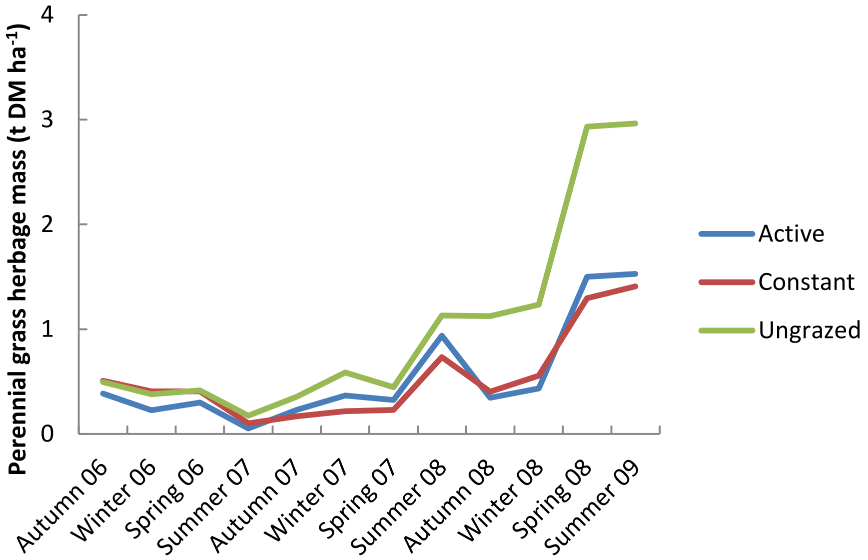


Figure 6 Perennial grass herbage mass for active, constant and ungrazed treatments on the lower slopes of the Trunkey Creek field site for the duration of the experiment.

The flupropanate treatments had the lowest perennial grass herbage mass on both the upper ($P < 0.001$; Figure 7) and lower ($P = 0.003$; Figure 8) slopes. On the upper slopes, the glyphosate treated plots had greater perennial grass herbage mass than the nil herbicide treatment whereas on the lower slopes, the glyphosate treated plots and nil herbicide plots were similar for the duration of the experiment.

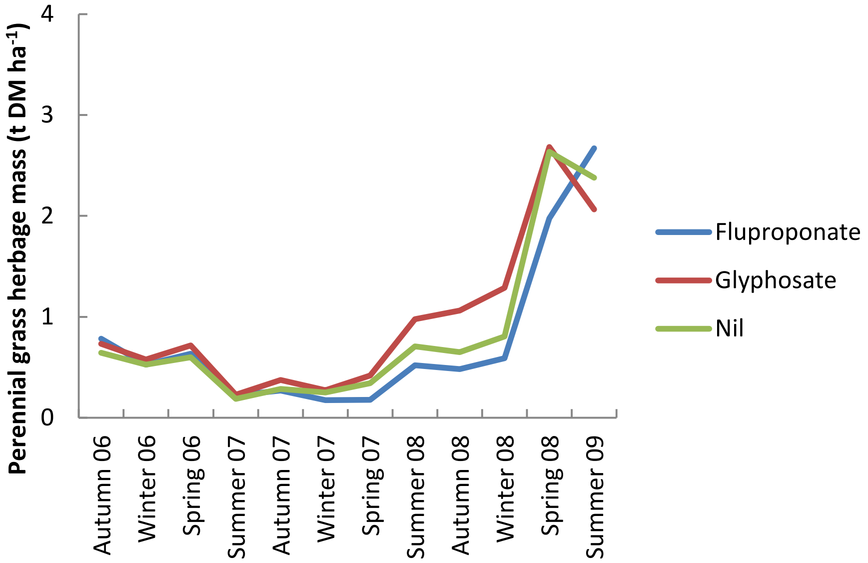


Figure 7 Perennial grass herbage mass for spot sprayed flupropionate, broadacre glyphosate and nil herbicide treatments on the upper slopes of the Trunkey Creek field site for the duration of the experiment.

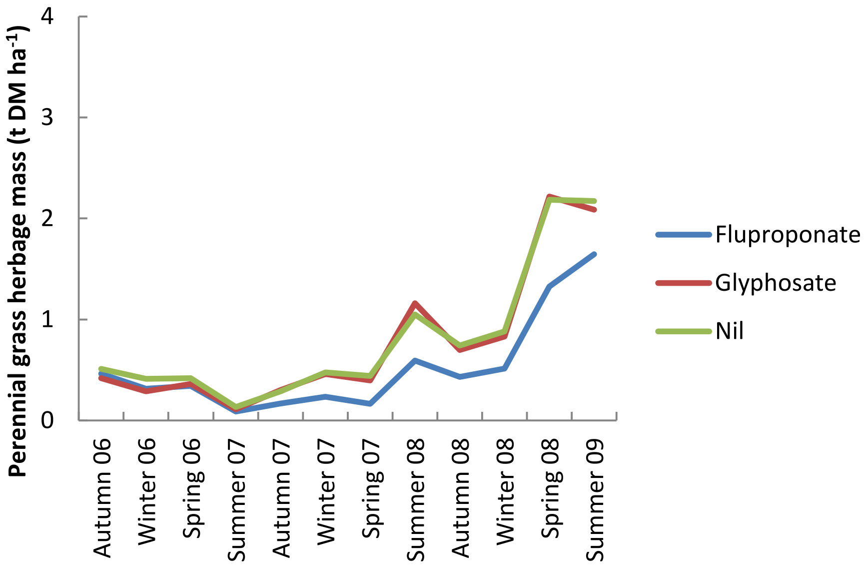


Figure 8 Perennial grass herbage mass for spot sprayed flupropionate, broadacre glyphosate and nil herbicide treatments on the lower slopes of the Trunkey Creek field site for the duration of the experiment.

Perennial grass : serrated tussock herbage mass ratio

The ratio of perennial grass : serrated tussock (PG:ST) herbage mass was used to examine how successful treatments were in controlling serrated tussock whilst taking into account the perennial grass herbage mass. Analysis of data from the Trunkey Creek site in 2006 showed that by increasing the proportion of perennial grass herbage mass present in winter, relative to the amount of serrated tussock, considerably restricted the growth of serrated tussock over the following six months ($P < 0.001$, adj. $R^2 = 29.3$; Figure 9). The ratio used in this way proved more insightful than simply looking at the actual biomass of serrated tussock and the desirable perennial grasses. A perennial grass : serrated tussock ratio of approximately 5:1 provides a safe buffer for management. Theoretically a 2:1 ratio would limit the growth of serrated tussock satisfactorily, but because this is required across an entire paddock and natural variability exists in a paddock, a ratio of 5:1 would ensure that the minimum target of 2:1 would be met across all areas of a paddock. This ratio works because it was derived from a paddock that was typical of many areas on the NSW Tablelands and hence the biomass values used in its derivation are not off scale relative to the target environment.

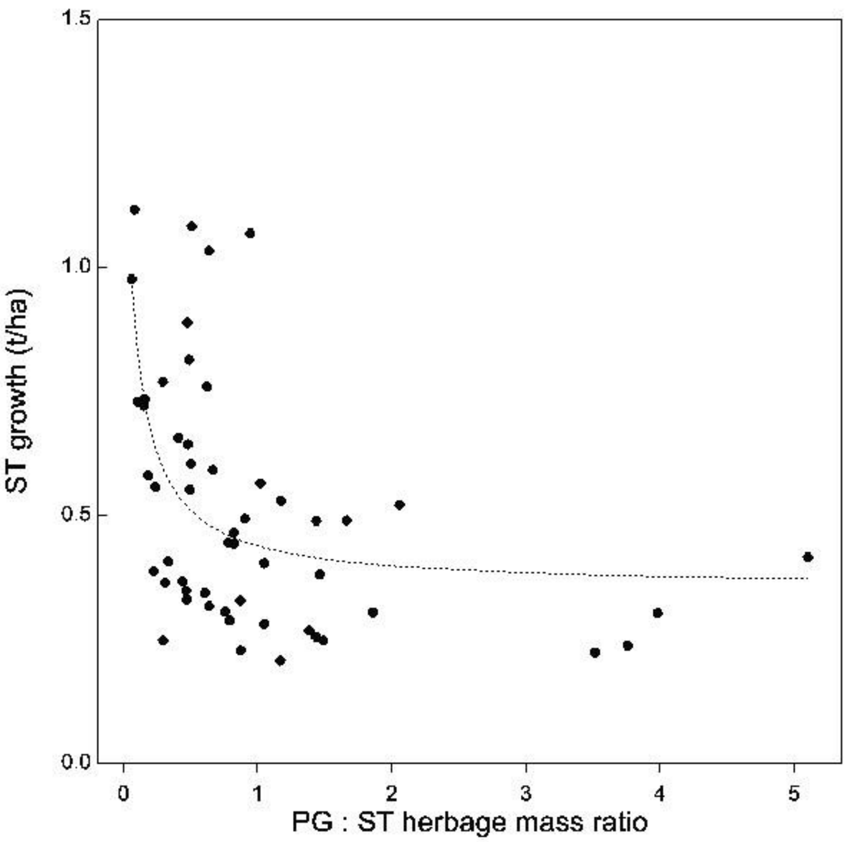


Figure 9 Relationship between serrated tussock growth (between winter 2006 and summer 2007) and the PG: ST ratio.

On upper slopes, the season x grazing and season x herbicide interactions for the PG:ST ratio were significant (P < 0.001; Figure 10 and Figure 11). The PG:ST ratio followed a similar trend for all treatments though it was generally higher for the constantly grazed or actively grazed treatment. The PG:ST ratio was better for flupropionate treated plots than for glyphosate or nil herbicide plots for the majority of the experiment.

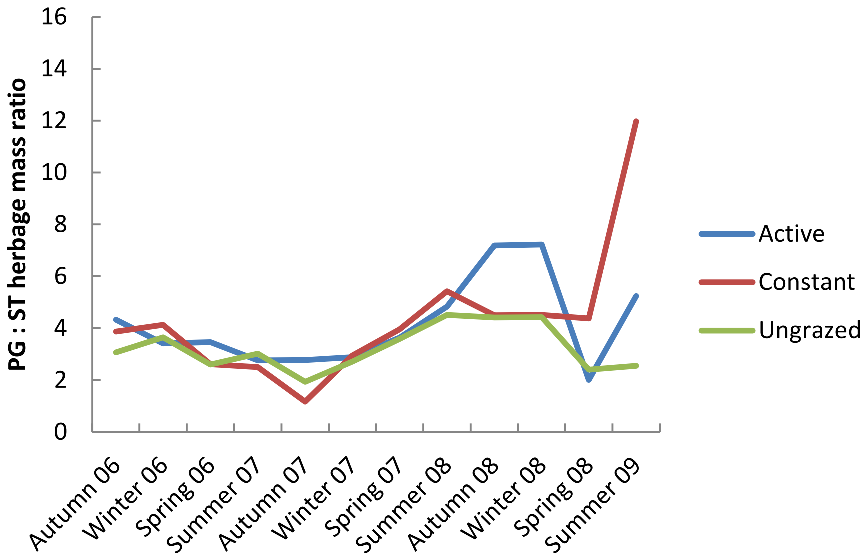


Figure 10 PG: ST ratio for active, constant and ungrazed treatments on the upper slopes of the Trunkey Creek field site for the duration of the experiment.

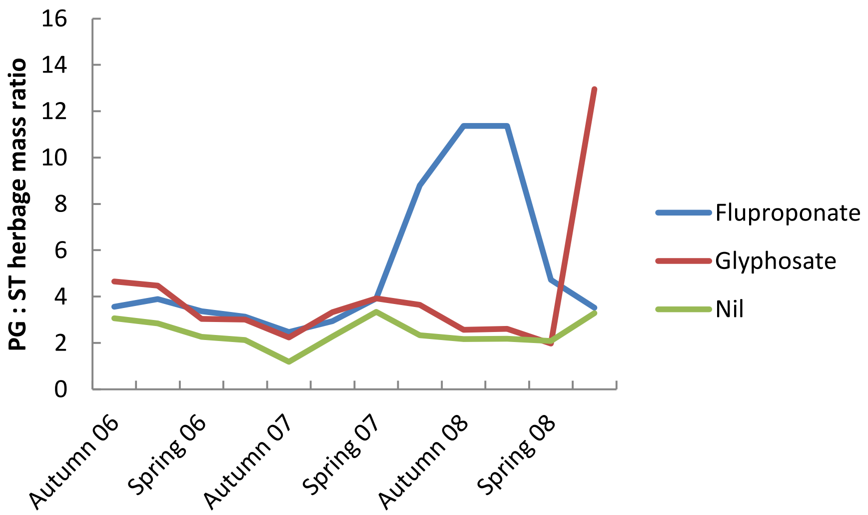


Figure 11 PG: ST ratio for spot sprayed flupropronate, broadacre glyphosate and nil herbicide treatments on the upper slopes of the Trunkey Creek field site for the duration of the experiment.

On the lower slopes, the season x herbicide treatment was significant for PG:ST ratio only ($P < 0.001$). The PG:ST ratio was better for the glyphosate treatment than the flupropronate or nil treatments for the majority of seasons after spraying compared to the other treatments (Figure 12).

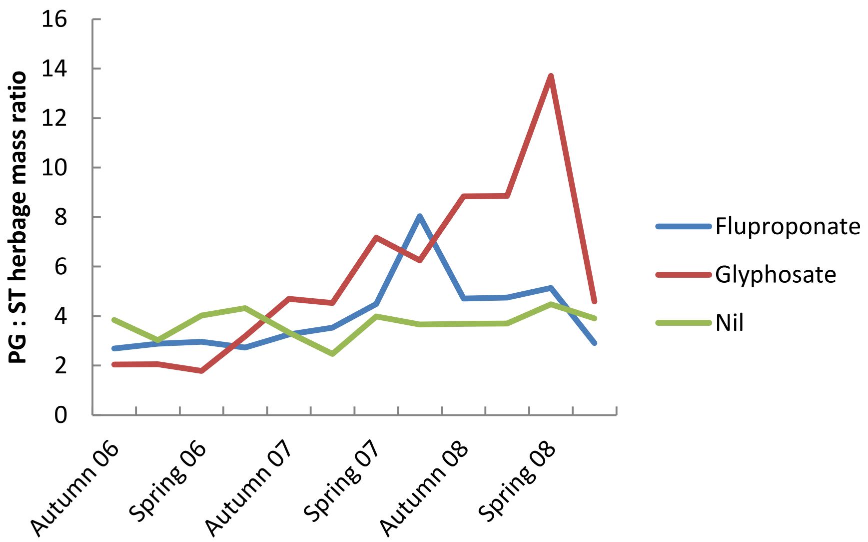


Figure 12 PG: ST ratio for spot sprayed flupropronate, broadacre glyphosate and nil herbicide treatments on the lower slopes of the Trunkey Creek field site for the duration of the experiment.

Discussion of how treatment combinations affected pasture competitiveness is detailed further in the following section.

4.1.1.3 Pasture matrix

Many techniques are available to test the statistical significance of treatments and a range of univariate and multivariate procedures were used in this project (more complete analyses will appear in scientific papers to be published). Generally a series of analytical methods are required to make useful judgements as to the efficacy of treatments. To provide a more readily useful means of judging the outcomes from each treatment a pasture competitiveness matrix was developed (). This framework was designed to enable a simple and effective assessment of the competitiveness of a pasture and provide targets for management. It was realised that a combined analysis was required that captured the relative interaction of serrated tussock with desirable native grass species and the total level of competition provided by the desirable native grasses. Other alternatives were explored *e.g.* amount of serrated tussock *Vs* amount of native grasses, but such diagrams did not help identify the combinations of species that management needs to aim for.

On the matrix diagram the vertical line for desirable native grasses was placed at 1.5 t DM ha^{-1}. This threshold was tested in the experiments as a criterion where few seedlings would survive the summer, a hypothesis that was substantiated. The horizontal line was placed at 5 (a ratio of perennial grass : serrated tussock herbage mass of 5:1) because analysis of data from the Trunkey Creek site identified this as the approximate ratio required, with a practical buffer for paddock variability, that perennial grasses kept serrated tussock growth at a minimum. An explanation of how to interpret the framework is given on the diagram ().

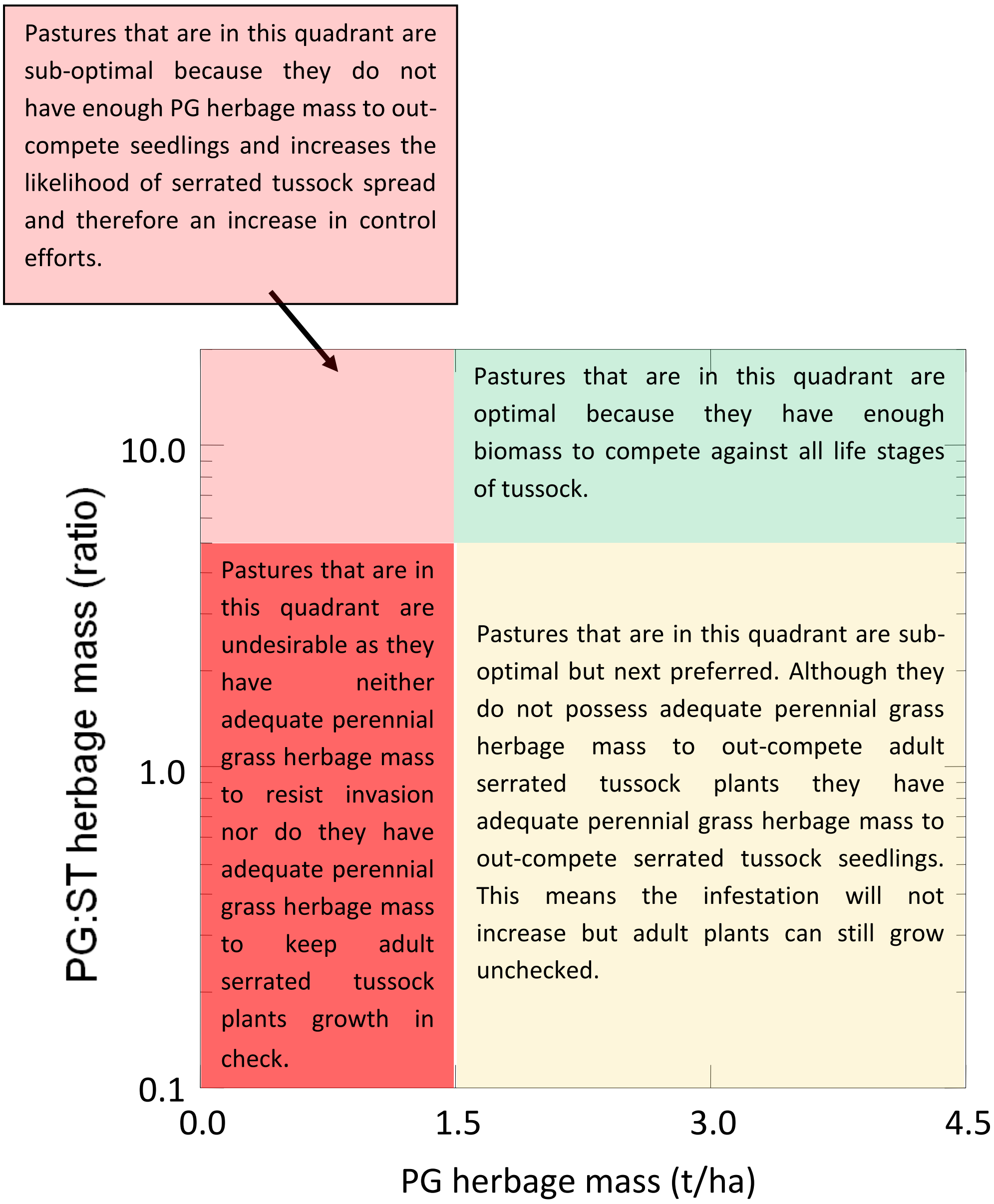


Figure 13. Interpretation of pasture matrix developed to assess the status of a serrated tussock invaded native pasture.

Treatment interactions

The positions of four treatment combinations for each sampling point for the entire experiment were plotted on the pasture competitiveness matrix (see Figures below) for comparisons to illustrate the trends, and success or otherwise, found. The treatments shown are the best management practice of active grazing and spot spraying to minimise collateral damage, the experimental technique of glyphosate applied when perennial grasses were not actively growing combined with active grazing, constant grazing with nil herbicide application (*i.e.* current management of the constantly grazed treatment by the participating landholder) and ungrazed with nil herbicide application (*i.e.* locking up the paddock).

No oversowing treatments have been included in the results presented as the native grass addition and superphosphate, sub-clover and ryegrass treatments had no discernible effect on pasture competitiveness, compared to the nil treatment (no addition of grass seed). The absence of any effects from the oversowing treatments was probably the result of the dry winter during which the treatment was applied resulting in few perennial grass or legume seedlings surviving. Oversowing is relatively expensive and while it has proved valuable in the past, the changing economic circumstances on farms means that lower cost strategies are now needed. Future work in this area is needed on oversowing perennial native grasses that are productive and competitive, which would require developing practices to obtain reliable sources of quality seed. Concurrent work in these landscapes is finding that common legumes are typically unable to establish over large areas, particularly on north facing slopes, due to poor soil moisture conditions (Hackney, *unpublished*).

For the upper slopes, a combination of a broadacre application of glyphosate (when the desirable perennial grasses were not actively growing) or spot spraying with flupropionate and active grazing was successful in achieving a competitive pasture (Figure 14). Initial changes were slow due to low rainfall, but by the end of the experiment the pasture was in an optimal competitive state. In contrast, constant grazing and nil herbicide application consistently had undesirable pastures for the entire experiment. Ungrazed treatments that had no herbicide application were less competitive than the actively grazed and herbicide treated treatments, though potentially were close to a desirable state by the end of the experiment.

These results show that tactical grazing management to maintain the herbage mass above 1.5 t DM ha^{-1}, achieved a more competitive pasture than no grazing, or continuous grazing. In addition, on upper slopes, a herbicide application that minimises disturbance to the desirable perennial grasses yet kills, or severely inhibits, adult serrated tussock plants is required to maintain pastures with optimal competitiveness.

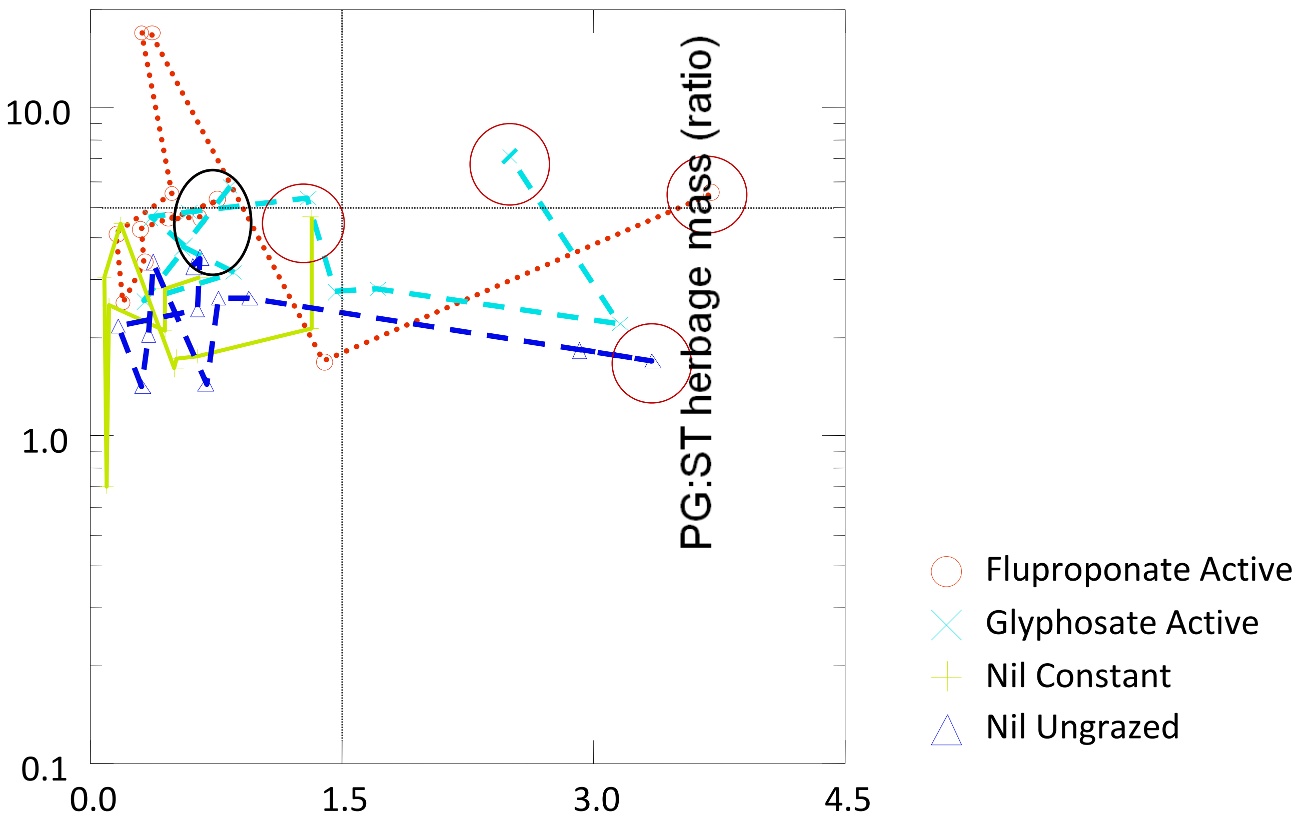


Figure 14. Pasture competition matrix for upper slopes treated with spot spray fluproponate and actively grazed, broadacre glyphosate and actively grazed, nil herbicide application and constantly grazed, and nil herbicide application and ungrazed. Points circled in black are initial sampling points in autumn 2006 and points circled in red are the final sampling points in summer 2009.

For pastures on the lower slopes, the herbicide treatments just fell short of the optimal ratio of desirable perennial grasses : serrated tussock, as the biomass of the desirable perennial grasses remained low for most of the experiment (Figure 3). The nil grazing, no herbicide treatment did accumulate herbage mass by the end of the experiment but serrated tussock still remained in those plots. The glyphosate herbicide treatment did significantly improve the ratio of desirable perennial grasses : serrated tussock, but not all tillers in adult serrated tussock plants were always killed by herbicide such that the PG: ST ratio did decline as serrated tussock recovered. Leaving the glyphosate herbicide treatment ungrazed and then following up with spot spraying to kill any tillers that survived could be required to achieve a good outcome. Alternatively, annual applications of glyphosate may kill all tillers. Annual applications of glyphosate until all tillers have been killed could actually be cost effective for large areas of moderately infested pastures because it takes less time than spot spraying, causes less collateral damage to perennial grasses than fluproponate applications and glyphosate is considerably cheaper (~$20 ha^{-1} v ~$60 ha^{-1} for glyphosate and fluproponate, respectively) Constantly grazed, nil herbicide plots remained in an undesirable state throughout. Thus while through these dry years the desirable pasture condition was not often reached, the actively grazed treatments were close and with continuing higher rainfall they may reach that target; as applied on the upper slopes (Figure 15). In this experiment herbicide treatments were only applied once and that may have limited responses. Annual herbicide applications coupled with active grazing treatments would seem to be a useful way forward.

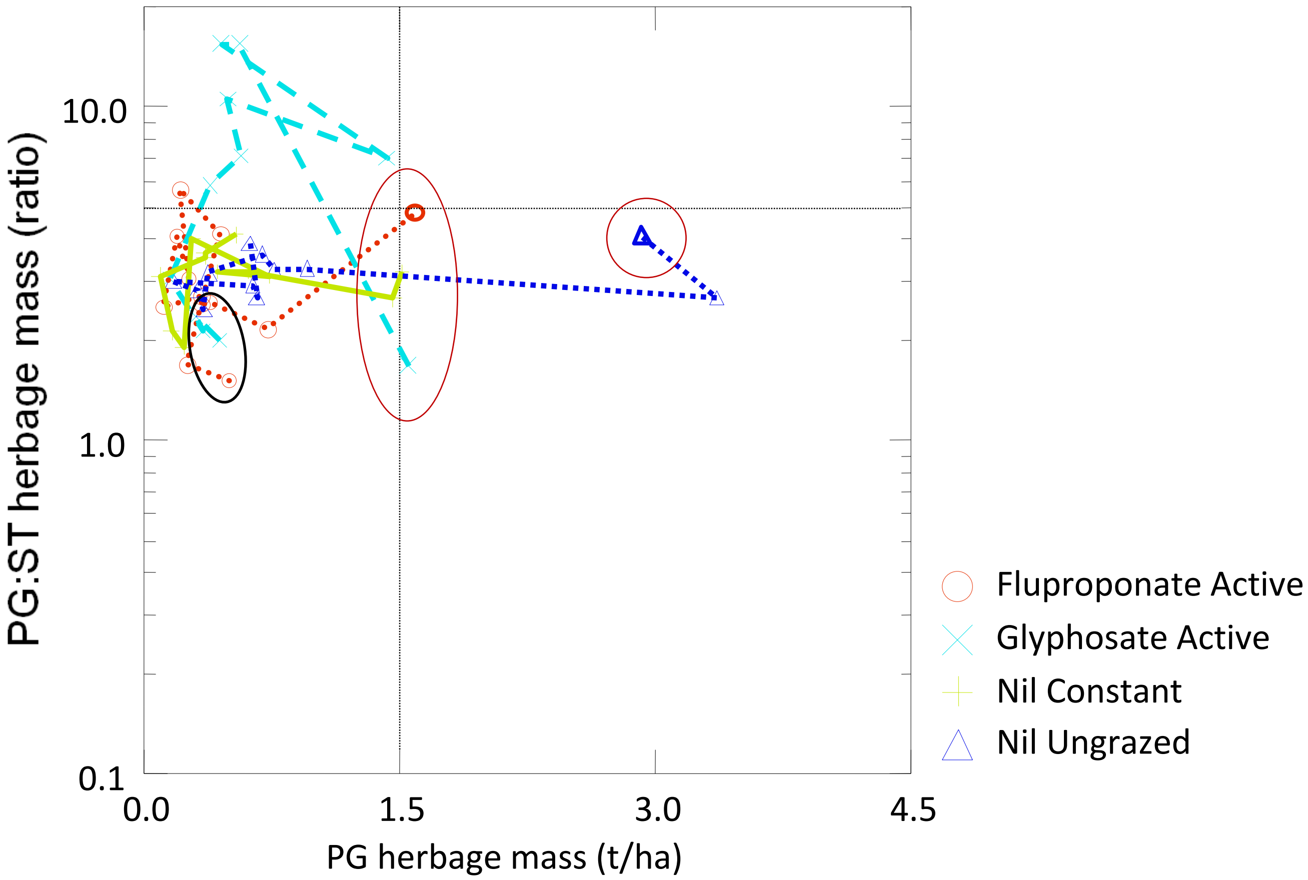


Figure 15. Pasture competition matrix for lower slopes treated with spot spray flupropoponate and actively grazed, broadacre glyphosate and actively grazed, nil herbicide application and constantly grazed, and nil herbicide application and ungrazed. Points circled in black are initial sampling points in autumn 2006 and points circled in red are the final sampling points in summer 2009.

It is proposed that managing serrated tussock using the 3T's (outlined below, Table 2) will over time, result in pastures being maintained in a state of optimal competitiveness by minimising disturbance, acting diligently after a period of deliberation. To move from one quadrant in the pasture competition matrix to the next, the application of grazing and herbicide must be used in combination and applied in a tactical, targeted and timely manner. Utilising these principles will kill adult serrated tussock plants and minimise re-invasion of serrated tussock plants. Applying these principles across a property allows maximum production from a paddock to be gained, whilst minimising control costs and resulting in a more profitable enterprise. These 3T's are useful for all paddocks except those that will require large inputs to revive pastures (*i.e.* high density infestations >50% serrated tussock, with a low existing perennial grass content). Economically viable options to revitalise these pastures are currently limited and requires more research.

Table 2. The 3T's for management of pastures invaded by serrated tussock.

	Grazing	Herbicide
Tactical	**Key message:** *Remove livestock when the herbage mass of desirable species drops to 1.5 t ha^{-1} at any time of the year.* Perennial grasses will outcompete most serrated tussock seedlings that germinate so to maintain competition graze only when the perennial grass herbage mass >2 t ha^{-1} and never let herbage mass fall below 1.5 t ha^{-1}.	**Key message:** *Use herbicides wisely* Herbicides need to be used tactically rather than as blanket applications in most serrated tussock infestations. Identify if you need to first reduce large patches (>40% tussock) with boom spray, focus on scattered plants with spot sprays, or if emerging seedlings can be controlled by resting paddocks over summer to outcompete serrated tussock seedlings.
Targeted	**Key message:** *Know your plant species and target management to encourage the desirable native grasses* If desirable species are declining, rest the paddock at the appropriate time. Use these grasses to outcompete serrated tussock by always leaving 1.5 t ha^{-1} of perennial grass herbage mass.	**Key message:** *Minimise herbicide damage to desirable species.* Aim to minimise damage to existing native perennial grasses and maintain competition by ensuring plants surrounding serrated tussock plants are not affected by the herbicides. You will need to know the negative effects herbicides have on native grasses. For example, red grass and kangaroo grass are tolerant of flupropanate whereas wallaby grass or microlaena will be killed in the vast majority of cases.

Timely	**Key message:** *Time rests to allow targeted desirable perennial grasses to flower, set seed, the seeds to mature and fall to encourage recruitment.* Ensuring perennial grass recruitment means pasture will remain competitive. If soils have hard surfaces a light scarifying can help native species establish (Thapa, *unpublished*). Minimise summer grazing to help native grasses limit survival of serrated tussock seedlings.	**Key message:** *Ensure serrated tussock plants are sprayed before September to stop seeding.* Herbicide must be applied each year in a tactical manner to ensure serrated tussock does not set seed. The best time to spot spray is anytime when the plant is first seen but to ensure a plant does not produce viable seed, spray all plants before the end of September

4.1.1.4 Economic analyses

Data on control costs and invasion rates collected by this project were combined with data from previous serrated tussock research to develop an economic model (outlined in 4.3.2) to evaluate the relative merits of alternative strategies for farm businesses. These data were incorporated into the decision support models produced as part of this project to aid farmers in selecting the better options for serrated tussock management.

The figures below show the output from two scenarios calculated by the economic model. Both scenarios are for a paddock that is 100 ha in size, is dominated by flupropionate sensitive native grasses and 50% of the paddock has a light infestation of serrated tussock while the remainder has no serrated tussock. Scenario 1 represents an active serrated tussock management strategy where the entire paddock is spot sprayed each year using flupropionate. Scenario 2 represents a reactive management strategy where no control is undertaken for 3 years until the density has increased and the entire paddock is then covered by a broadacre application of flupropionate in the 4th year. Scenario 1 maintains a minimum of 1.5 t ha^{-1} of perennial grass herbage mass while scenario 2 maintains only 0.4 t ha^{-1} of perennial grass herbage mass.

The net annual returns for each scenario are shown in Figure 16. Returns in year 1 are greater for scenario 2 and this is due to the cost of spot spraying the entire paddock. Returns for scenario 2 (reactive management) decline however due to an increase in serrated tussock invasion and subsequent losses in production. Net annual returns for scenario 2 in year 4 are negative and this is the result of a broadacre application of flupropionate. Returns in scenario 2 do not return to original levels because the application of flupropionate caused a high level of mortality of perennial grasses that results in lower production in following years and the low level of herbage mass (0.4 t ha^{-1}) results in re-invasion. No control is done to manage re-invasion so another broadacre application of flupropionate is required in year 7. In contrast, the net annual returns of scenario 1 (proactive management) results in annual returns increasing because, once the initial light infestation has been controlled and a higher residual herbage mass is left in the paddock, less time is required each year to keep invading plants in check. The accumulated returns over the same period are shown in Figure 17 and shows that for scenario 1 the accumulated returns over the 10 year period are approximately \$150 ha^{-1} but for scenario 2 the accumulated annual loss for the paddock is approximately \$300 ha^{-1}.

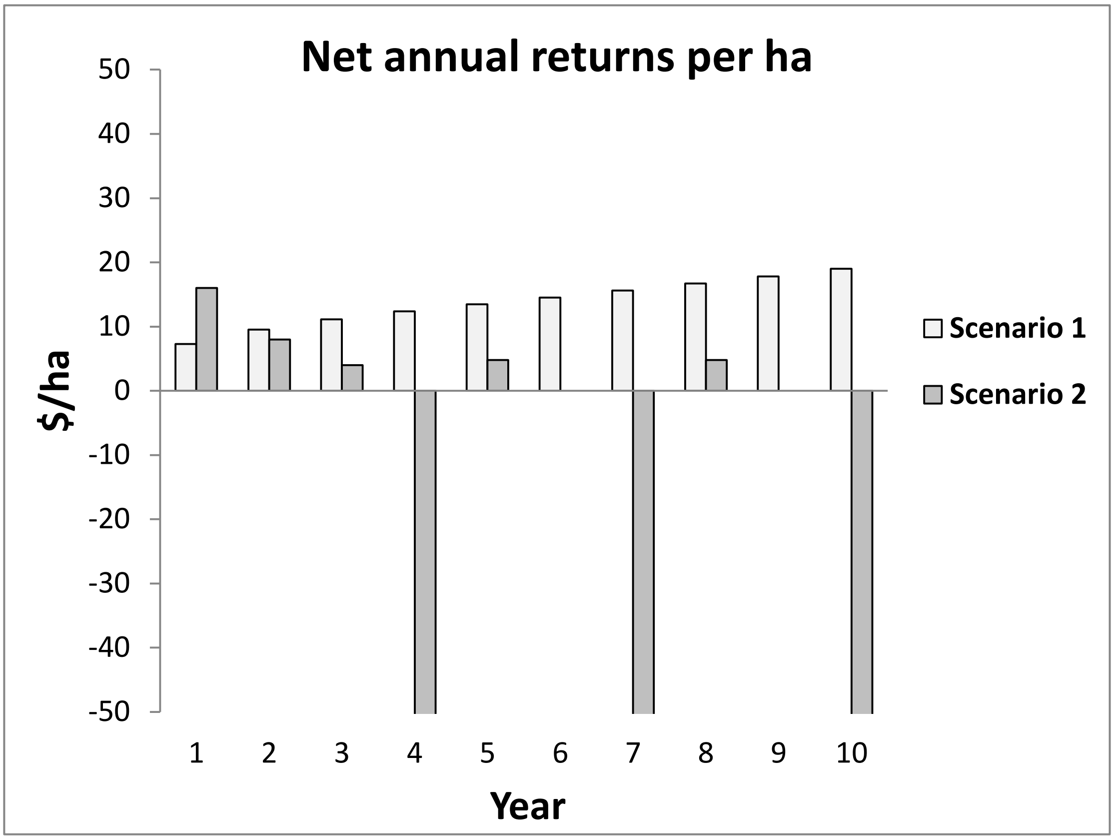


Figure 16. Net annual returns per ha for scenario 1 (proactive management *i.e.* annual spot spraying) and scenario 2 (reactive management *i.e.* aerial herbicide spraying every three years when the infestation becomes too dense) generated by the economic tool.

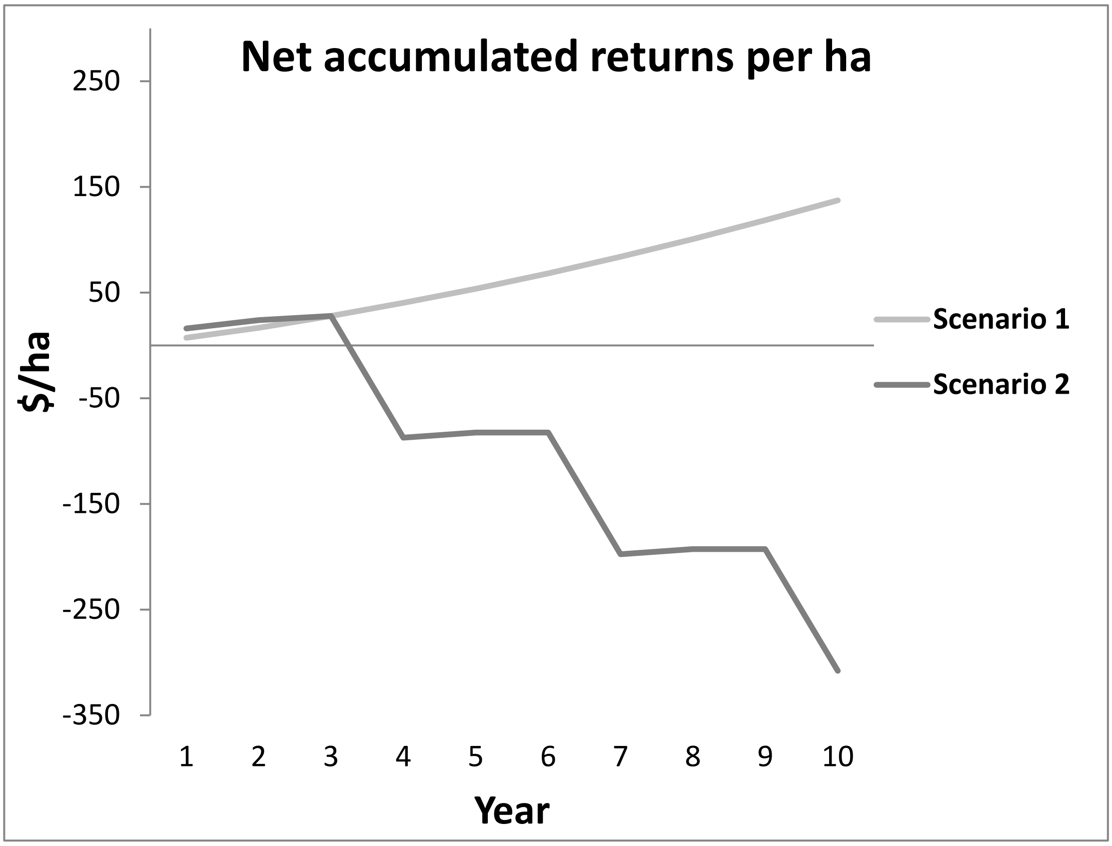


Figure 17. Net accumulated returns per ha for scenario 1 (proactive management *i.e.* annual spot spraying) and scenario 2 (reactive management *i.e.* aerial herbicide spraying every three years when the infestation becomes too dense) generated by the economic tool.

4.1.2 Effect of defoliation on competition between serrated tussock and native grasses.

Defoliation of neighbouring species and fertility effect serrated tussock biomass

Serrated tussock plant growth was affected by the competitiveness of the neighbouring plants and soil fertility (Figure 18). Intact *M. stipoides* plants had the greatest effect on serrated tussock growth followed by defoliated *M. stipoides*. Undefoliated *A. linkii* had a smaller effect and defoliated *A. linkii* was least effective in suppressing growth of serrated tussock. The same trends occurred at high and low fertility, though they were not always significant.

The below ground biomass of serrated tussock was significantly affected by competition from *M. stipoides* and *A. linkii* (P = 0.04, Figure 19)

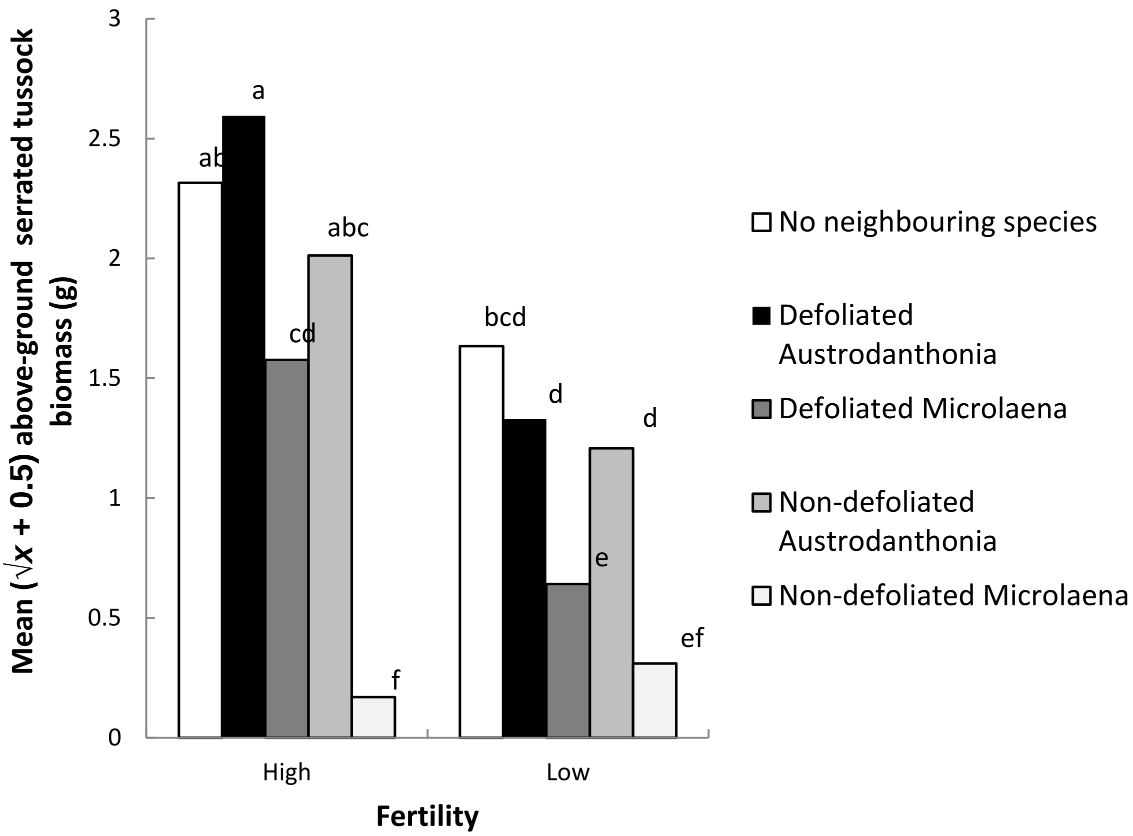


Figure 18. Mean (√*x* + 0.5) above-ground biomass of serrated tussock grown in high and low fertility treatments without neighbours or with defoliated or undefoliated *M. stipoides* (Microlaena) or *A. linkii* (Austrodanthonia). Bars with the same letter do not differ significantly by the LSD (P=0.05).

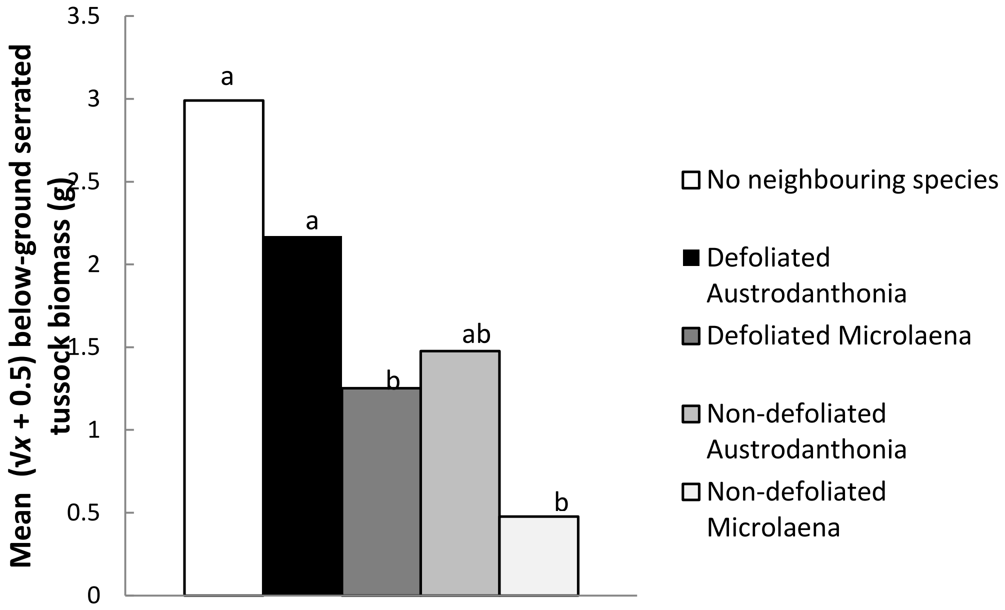


Figure 19. Mean (√*x* + 0.5) below-ground biomass of serrated tussock grown without neighbours or with defoliated or undefoliated *M. stipoides* (Microlaena) or *A. linkii* (Austrodanthonia). Bars with the same letter do not differ significantly by the LSD (P=0.05).

Defoliation of neighbouring species and fertility effects native grass biomass

Above-ground *M. stipoides* biomass was always greater than *A. linkii* whether grown alone, defoliated with a neighbour or undefoliated with a neighbour except for defoliated plants in the low fertility treatment (Figure 20). The presence of a neighbouring plant had no effect on the above-ground biomass of undefoliated plants of both species compared to those that were grown without a neighbour in both fertility treatments. This result indicates that establishing *N. trichotoma* seedlings are very poor competitors, an observation supported by previous research (Badgery *et al.* 2006).

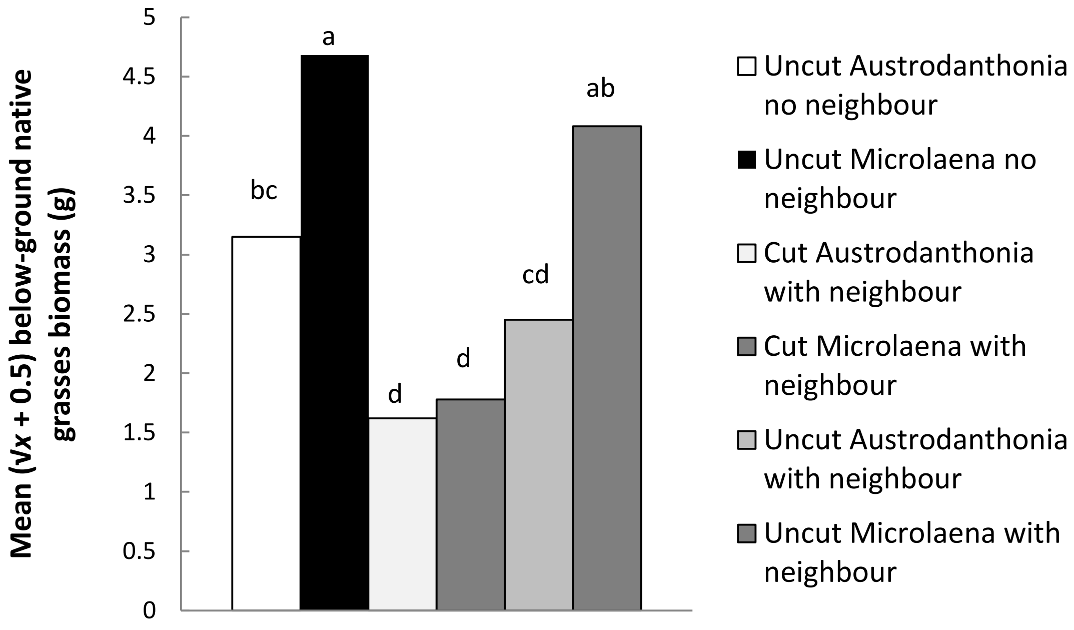


Figure 20. Mean (√*x* + 0.5) above-ground biomass of defoliated or undefoliated *M. stipoides* (Microlaena) or *A. linkii* (Austrodanthonia) grown without a neighbouring serrated tussock plant grown in high and low fertility treatments. Bars with the same letter do not differ significantly by the LSD (P=0.05).

These results indicate that where possible to suppress growth of serrated tussock, *M. stipoides* should be encouraged. *M. stipoides* is more often found in lower slopes where moisture and fertility is generally higher. *A. linkii* is not very competitive especially if cut *i.e.* grazed. Unfortunately *Austrodanthonia* spp. are more common on upper slopes. In those instances an active grazing strategy is arguably warranted to minimise utilisation of *Austrodanthonia* spp. during the summer when the maximum competitiveness on serrated tussock populations needs to be maintained. While this pot experiment suggests the level of competitiveness that *A. linkii* can exert is limited, in the field the actively grazed treatments did over time result in a reduction in the proportion of serrated tussock (Figure 2) showing that even a low level of competition can be important in regulating the growth of serrated tussock.

4.1.3 Managing recruitment

No survival of serrated tussock or native grasses seedlings occurred over the 2006-2007 summer, as a result of the drought and competition from established plants. Over the summer of 2007-2008 no survival of native grasses occurred and recruitment of serrated tussock only occurred on the lower slopes. It is unlikely that this result suggests that serrated tussock has an advantage over native perennial grasses under dry conditions and it is more the result of a much greater number of seeds in the seedbank. Data for the lower slopes, analysed to account for spatial variation, showed that grazing and herbicide application had a significant (Table 3 $P<0.05$) effect on the numbers of serrated tussock seedlings that established. Constantly grazed treatments had the highest rate of weed establishment followed by ungrazed and then actively grazed plots, which were not grazed during the more stressful summer period. Even where herbicide wasn't used, seedlings still established but weed establishment was higher in plots that were treated with herbicide. The active grazing strategy was clearly the most successful and did combine successfully with spot spraying with flupropanate to prevent any serrated tussock seedlings surviving. *M. stipoides* also has the advantage of adult plants being tolerant to glyphosate.

Table 3. Mean numbers of seedlings m^{-2} recorded for treatments on the lower slopes of the Trunkey Creek field site in autumn 2008. Means within treatments followed by different letters differ significantly at P=0.05 using LSD.

Seedling number (m^{-2})	**Nil herbicide**	**Fluproponate**	**Glyphosate**	**Means**
Constantly grazed	2.19	4.20	4.80	**3.73c**
Ungrazed	0.37	1.91	1.45	**1.23b**
Actively grazed	0.00	0.00	0.78	**0.04a**
Means	**0.76a**	**1.52b**	**2.34b**	

The data for 2007-8, when treatment effects were clearly established, was analysed using a regression tree (Figure 21) which indicated that the greatest numbers of serrated tussock seedlings established in quadrats where bare ground was greater than ~84%, the biomass of broadleaf plants was greater than 0.17 t ha^{-1} and serrated tussock biomass was greater than 0.66 t ha^{-1}. The link between bare ground and serrated tussock establishment is well recognized however the link between broadleaf plant biomass and serrated tussock biomass has not been previously reported. Broadleaf plants require bare ground to establish and the results (Table 3) showing the application of herbicide increased serrated tussock recruitment suggest that these treatments caused a disturbance event that increased bare ground and, consequently, the recruitment of serrated tussock and broadleaf species. The small amount of broadleaf biomass associated with more serrated tussock seedlings may simply reinforce the amount of bare ground available for recruitment. This indicates that when broadleaf species are increasing in a paddock the level of disturbance is also increasing and more serrated tussock could then be expected. The association between seedling recruitment and serrated tussock biomass may be because of an increase in serrated tussock biomass as a result of recruitment. These results further support the current best management practices of minimising disturbance to maintain the resilience of a native pasture to invasion. Badgery *et al.* (2008) reported an association between perennial grass biomass and seedling recruitment however those results are from a year with more rainfall than in this study. It might be that in years with minimal rainfall the amount of bare ground is more important than competition from surrounding perennial grasses as the established grasses are too small and sparse to be competitive. These results indicate that bare ground and the presence of broadleaf species are associated with serrated tussock invasion and can be used to indicate pastures that are susceptible to invasion in dry years.

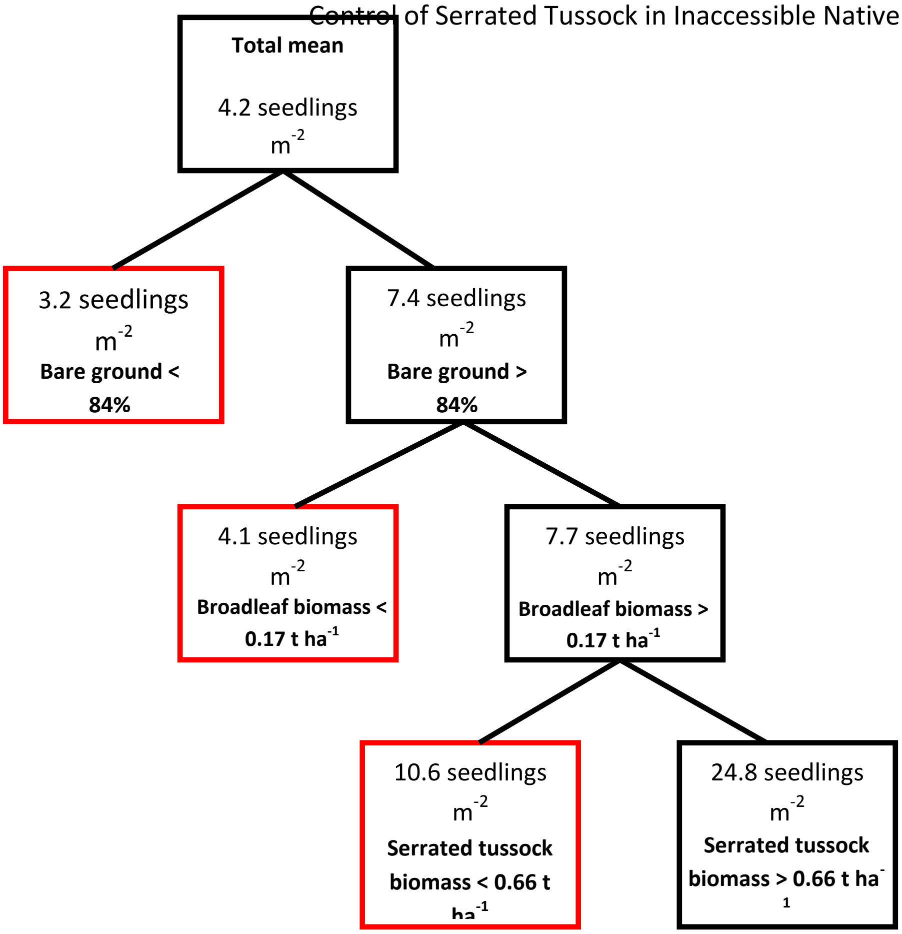


Figure 21. Decision tree, based on regression analyses, for variables across all treatments associated with serrated tussock seedling recruitment m^{-2} for the lower slopes of the Trunkey Creek field site during the drought of 2007-8. The variables listed were the only ones of the many measured that contributed at least 5% to the total proportional reduction in error.

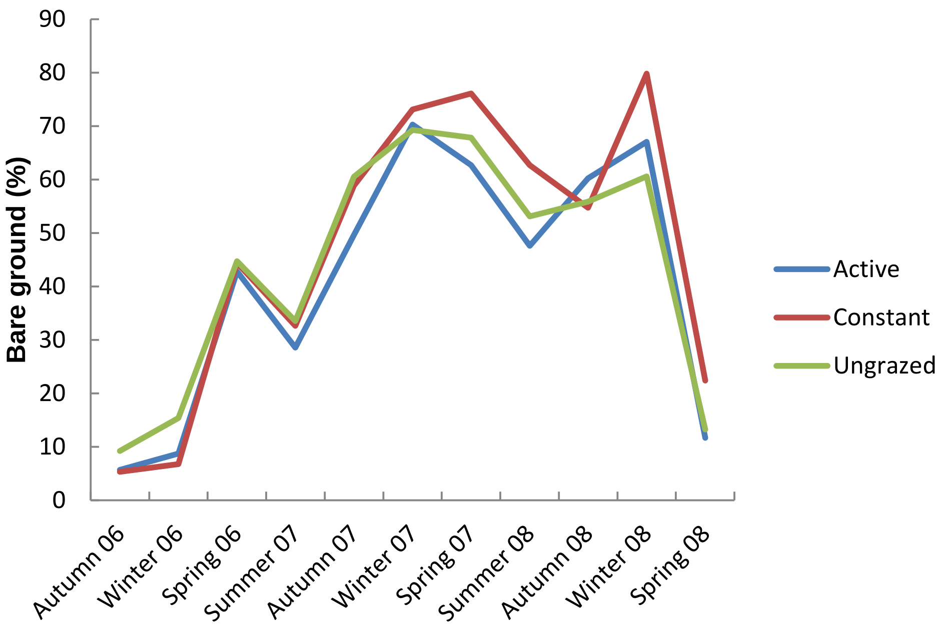


Figure 22. Percentage bare ground for actively, constantly and ungrazed plots on the lower slopes at Trunkey Creek for the duration of the experiment.

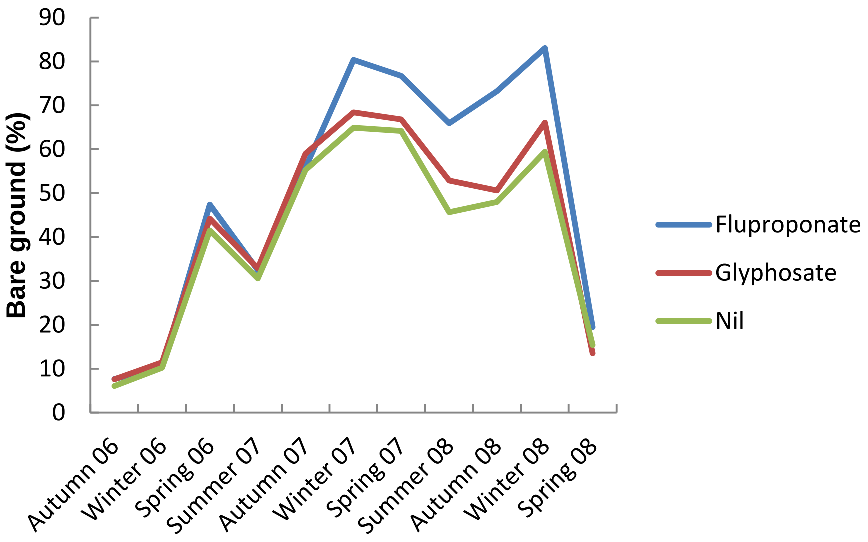


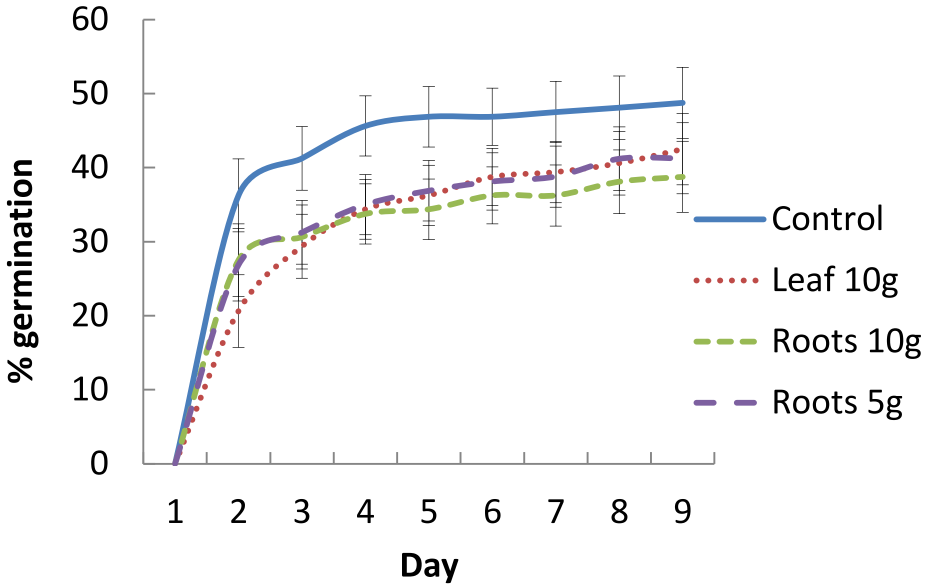
Figure 23. Percentage bare ground for nil, spot sprayed flupropionate and broadacre glyphosate treated plots on the lower slopes at Trunkey Creek for the duration of the experiment.

Analysis showed that the time period x herbicide and time period x grazing interactions were significant ($P < 0.001$) for the lower slopes and that constantly grazed treatments and flupropionate sprayed treatments had the greatest percentage of bare ground overall (Figure 22 and Figure 23). These two management strategies are likely to lead to greater invasion rates. Seedling numbers shown in Table 3 show lower seedling numbers in flupropionate treated plots however this would likely be due to the residual effects of flupropionate and would not be a long term effect.

The oversowing treatments in the main field experiment did not achieve any significant increase in competition for serrated tussock as few plants established under the dry conditions that prevailed. The existing swards provided sufficient competition to limit seedling recruitment and reduce the vigour of existing serrated tussock plants when managed appropriately. What would happen in wetter years is uncertain. No data is available to indicate if the existing native grasses would exert enough competition to achieve similar results. In such years rainfall over summer may still be restricted to a few rainfall events and in consequence the dry periods between events could result in seedling death provided sufficient competition occurs. Future work may though show that sowing fast growing pasture species, may still prove to be a useful addition to the tactics available for serrated tussock management.

4.1.4 Allelopathy

This experiment was done to determine whether the presence of serrated tussock leaf litter and roots had any effects on the establishment of native grasses (*Chloris truncata* and *Microlaena stipoides*) and subsequent growth of those species. The percentage of germinated seeds treated with aqueous extracts prepared from 5 or 10 g of roots or 10 g leaves were significantly less than the control from days 3 until measurements stopped at



day 9 (

Figure 24). There were only minor differences between the three extracts. By day 3 the seeds treated with extracts had only 75% of the germination for seeds in water and that approximate difference remained to day 9. The main effect of species was significant ($P<0.001$) with the numbers of germinated seeds significantly greater for *C. truncata* than for *M. stipoides* (data not shown).

These results indicate that the aqueous extracts from serrated tussock were mildly phytotoxic. Additional extracts prepared from 5 g of leaf material did not however affect seed germination. This suggests that the concentration of allelopathic compounds may differ between roots and leaves as has been shown to occur in *Oryza sativa* and *Triticum aestivum* (Kong *et al*. 2004; Wu *et al*. 2000). Although the differences in germination were not as large as applies with other species where almost no germination occurs, they may be of practical significance by reducing establishment of native grasses in degraded pastures infested with serrated tussock that are trying to be rejuvenated by establishing these grasses through naturally occurring recruitment from low population densities and limited seed production.

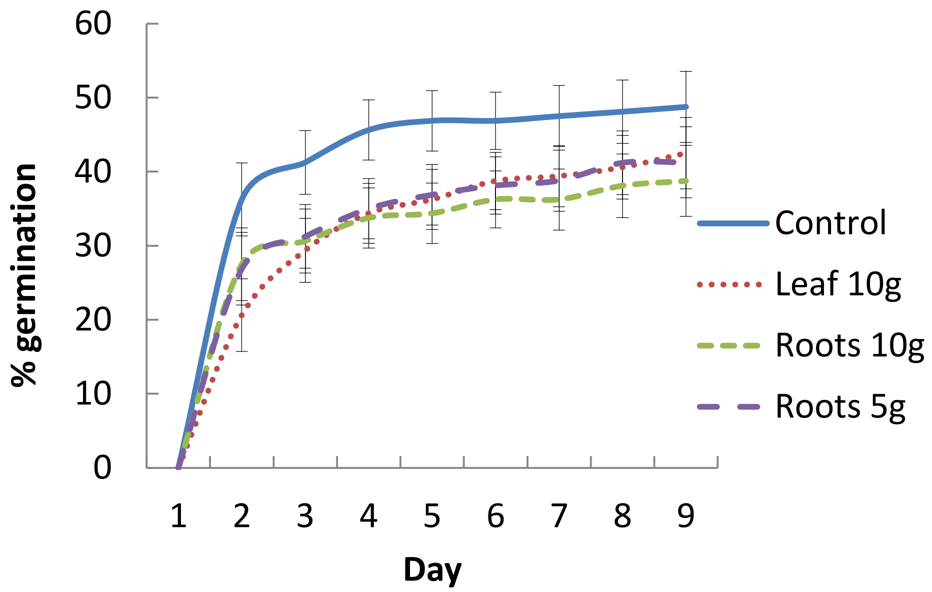


Figure 24. Percentage germination of *C. truncata* and *M. stipoides* in teas made with 10g leaf/100ml water, 10g roots/100ml water, 5g roots/100ml water, water only (control). Error bars indicate significant differences.

Plants were then grown in pots that had litter from serrated tussock added. The species x litter interaction was significant for above-ground biomass (P=0.009, Figure 25). *C. truncata* grown with 4 t ha^{-1} of litter had the largest above-ground biomass and *C. truncata* with 0 or 2 t ha^{-1} litter had the next largest. The above-ground biomass of *M. stipoides* was lower than *C. truncata* and did not differ between litter treatments (data not shown). The species x litter interaction was significant for below-ground biomass (P=0.041, Figure 26). *C. truncata* grown with 2 or 4 t ha^{-1} of litter had a greater below-ground biomass than *C. truncata* grown with 1 t ha^{-1}. The below-ground biomass of *M. stipoides* did not differ between litter treatments. *C. truncata* had a significantly greater plant height (P<0.001), leaf width (P<0.001), above-ground biomass (P<0.001) and below-ground biomass (P<0.001), and significantly fewer tillers (P<0.001) and leaves (P<0.001) than *M. stipoides* (data not shown).

The results from this experiment suggest that any allelopathic effects of serrated tussock are small. It showed that relatively low amounts of *N. trichotoma* litter reduced the above-ground biomass of *C. truncata* relative to the control suggesting that relatively small amounts of allelopathic compounds in leaves may have a negative influence on *C. truncata* seedlings. In contrast, when 4 t litter ha^{-1} were present, the above-ground biomass of *C. truncata* was greater than the control, a finding similar for sub clover production with phalaris litter by Leigh *et al.* (1995a). This increase may have been due to the litter acting as a mulch, (*i.e.* reducing the rate at which soil dries and retaining soil moisture) however the absence of any benefit to *M. stipoides* indicates that higher concentrations of compounds found in litter may have a stimulatory effect on *C. truncata.* Allelopathic effects are species specific (Renne *et al.* 2004) so it is common for one species to be affected by allelopathic chemicals whilst another is largely unaffected. The experiment found that 4 t of *N. trichotoma* litter ha^{-1} increased above-ground biomass by six percent. This amount of litter would, however, only be found in very dense infestations where the density of native perennial grasses is low. It is unlikely that the presence of litter would be beneficial as these levels of litter occur in dense infestation where production from native grasses is minimal.

The depression in growth at the lowest levels of litter was in contrast to the response at higher levels. The cause is unknown but would be worthy of further investigation as it may suggest some nutrient restrictions from microbial activity in the limited litter. Previous work (Badgery 2006) showed that sugar treatments increased the C:N ratio in the soil such that growth of serrated tussock was then depressed and no seedlings recruited.

Considering that most allelopathic compounds have an effect on multiple species further work is required to determine the effect of allelopathic compounds on other native perennial grasses (*Austrodanthonia* spp., *Bothriochloa* spp. and *Elymus* spp.). Work is required to examine the longevity of allelopathic chemicals in serrated tussock.

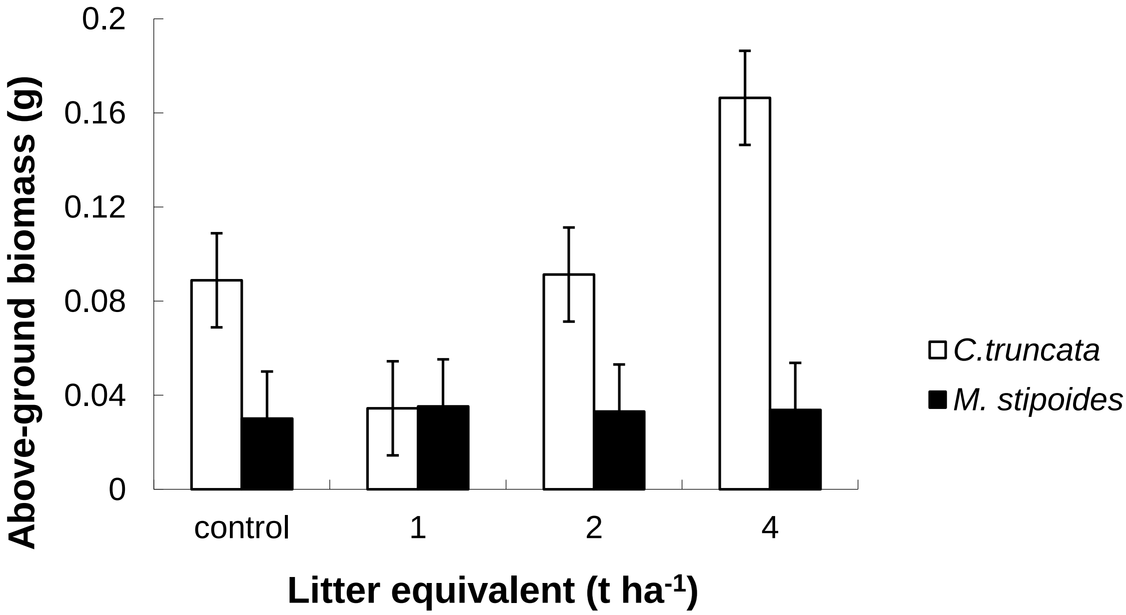


Figure 25. Above-ground biomass of *C. truncata* and *M. stipoides* grown with the equivalent of 0, 0.5, 1 and 4 t of leaf litter per ha on the soil surface. Error bars indicate significant differences.

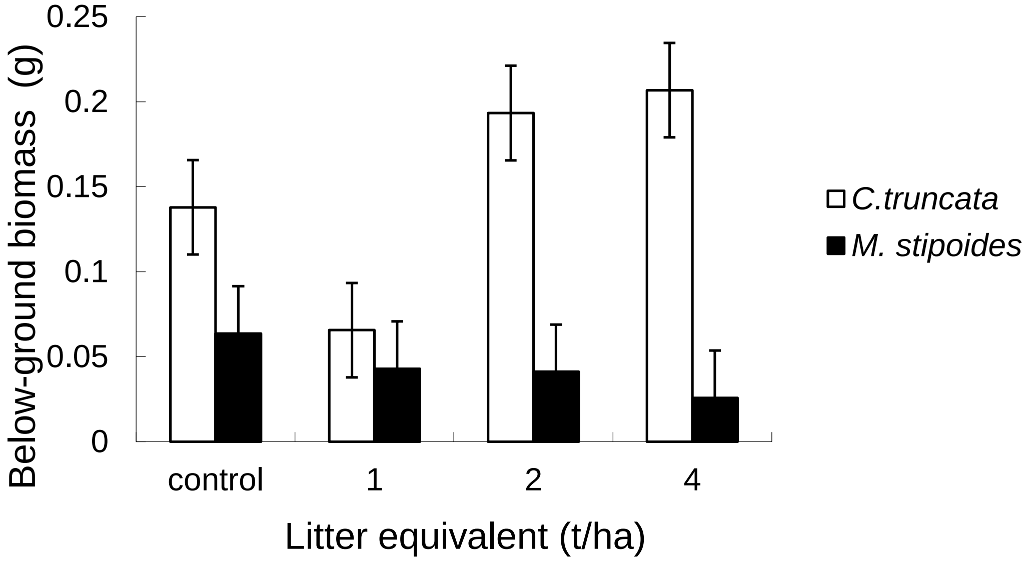


Figure 26. Below-ground biomass of *C. truncata* and *M. stipoides* grown with the equivalent of 0, 1, 2 and 4 t of leaf litter per ha on the soil surface. Error bars indicate significant differences.

4.2 Novel control methods

4.2.1 Gibberellic acid responses

Gibberellic acid (GA) causes etiolation of plant stems and leaves. It was hypothesised that etiolation from the application of GA may improve the feed quality of serrated tussock and make it more palatable to stock, enabling grazing pressure to be increased and adult plants to be controlled. In a preliminary study *Chloris truncata* and *Microlaena stipoides* were used to investigate the response of a C4 and a C3 native grass to GA and to resolve dose rates for a larger field study. Three concentrations of GA and a control (water) were sprayed onto *C. truncata* and *M. stipoides* plants at 16 and 21 weeks of age and the effects on forage quality analysed. The applications of GA resulted in a significant increase in the fibre content of the grasses (Figure 27) but had no significant effect on digestibility, dry matter production, metabolisable energy, non-detergent fibre or protein content. The increase in fibre reduced feed quality. As serrated tussock is well-renowned for a very high fibre content to start with, it was then decided that this approach was unlikely to be justified and this line of investigation was not proceeded with.

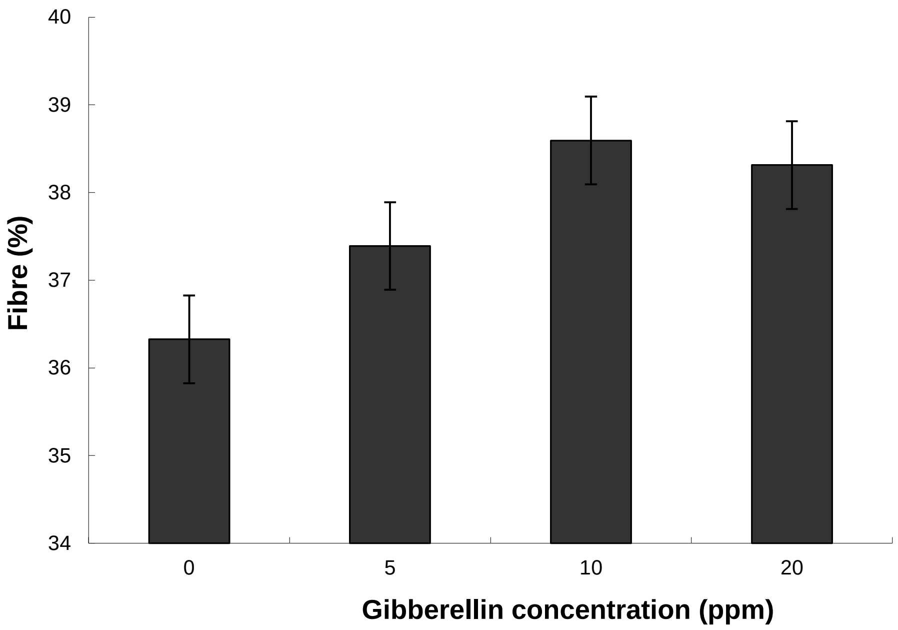


Figure 27. Percent fibre for *C. truncata* and *M. stipoides* sprayed with 0, 5, 10 and 20 ppm of gibberellic acid. Error bars indicate significant differences.

4.2.2 Thatchbusta®

Thatchbusta® has been promoted as aiding the breakdown of thatch and aiding in the control of serrated tussock. This trial was combined with a spray program done by a landholder on the NSW Central Tablelands on marginal country used for fine wool production. The landholder hoped that mixing Thatchbusta® and nutrients with flupropionate would minimise the effects of flupropionate on existing species and reduce the time taken for the pastures to recover. The trial was monitored for 12 months at which point there was no evidence that the Thatchbusta® treatment (Figure 28d) had any advantage over the conventional broadacre application of flupropionate (Figure 28c). Not only did the Thatchbusta® treatment show little benefit, the cost of \$330 ha^{-1} compared to applying flupropionate only (\$120 ha^{-1}) made this an uneconomic option for control of serrated tussock in these areas. For these reasons, monitoring the trial ceased after 12 months.

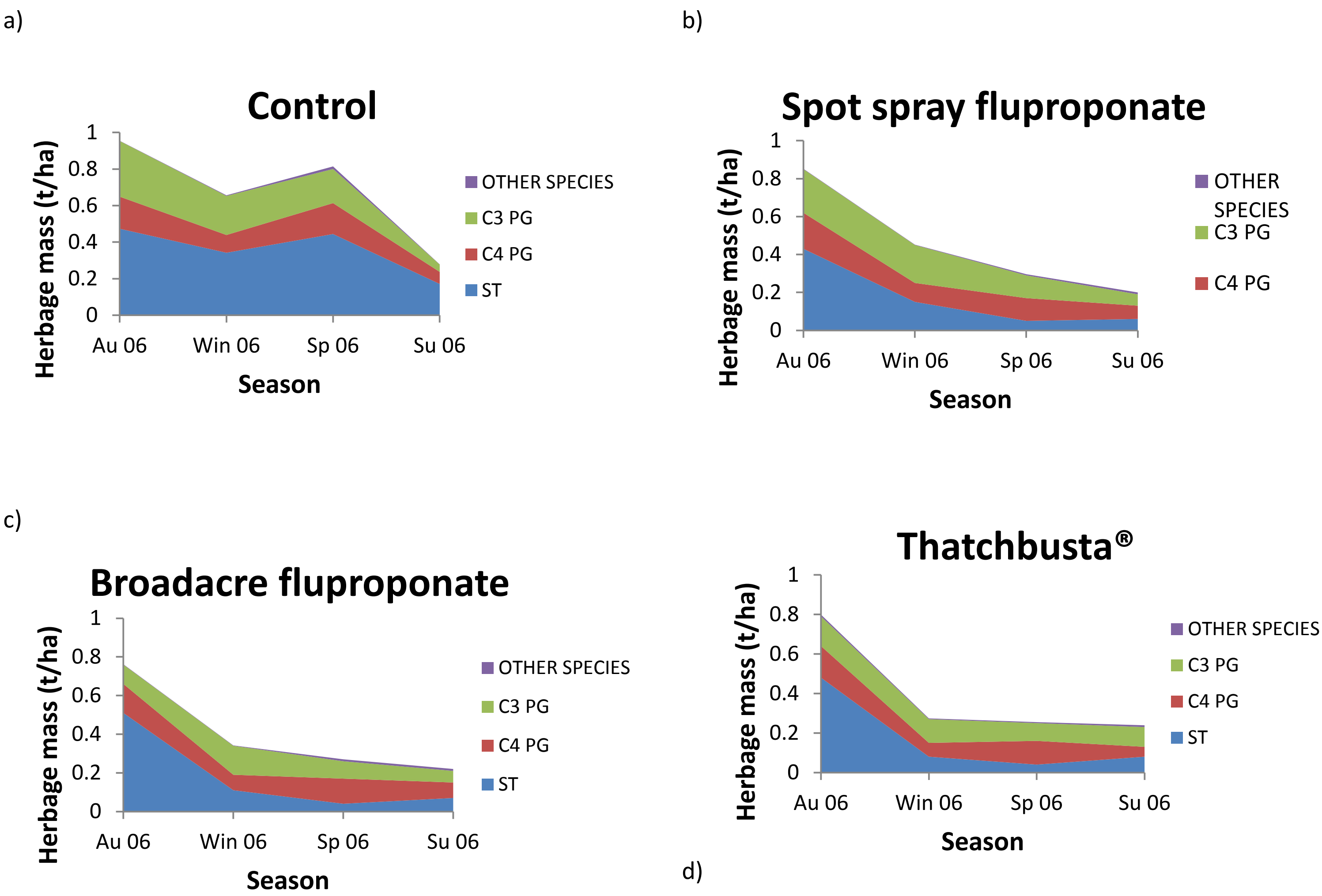


Figure 28. Changes in functional groups over four seasons for plots either a) unsprayed (control) b) spot sprayed with fluproponate c) broadacre fluproponate or d) Thatchbusta®, fluproponate and nutrients.

4.2.3 The effect of silicon on photosynthesis in grasses

Previous research (Hattori *et al.* 2008; Nwugo and Huerta 2008) has shown that increased soil silicon affected photosynthetic activity of grasses so an experiment was done to examine whether any effects of silicon on photosynthesis could be exploited to help manage serrated tussock. This experiment showed that silicon had no effect on the photosynthetic activity of serrated tussock or *Microlaena stipoides* supporting other research that also failed to find a significant change in photosynthetic activity (Hattori *et al.* 2008). The rate of photosynthesis was dependent on species (Figure 29; P<0.001), and interestingly serrated tussock had a greater photosynthetic rate than *M. stipoides.* Further, well watered plants had a greater photosynthetic rate than water stressed plants (Figure 30; P=0.033). The maximum capacity to transport electrons (J_{max}) also differed between species (P=0.031) with serrated tussock having a greater ability to transport electrons than *M. stipoides* (Figure 31) supporting the other results that serrated tussock has a greater capacity for photosynthesis than *M. stipoides.*

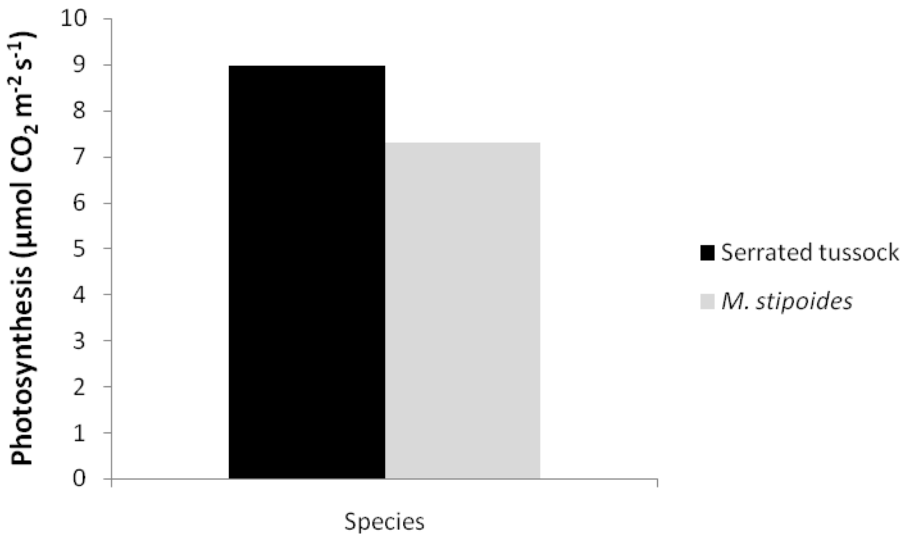


Figure 29. Mean photosynthetic activity of serrated tussock and *M. stipoides* grown under all conditions.

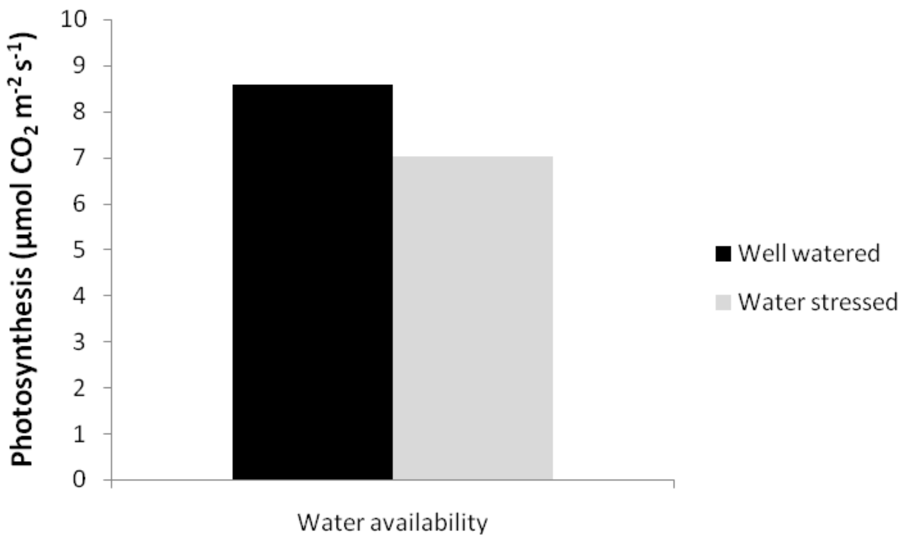


Figure 30. Mean photosynthetic activity of serrated tussock and *M. stipoides* grown in well watered and water stressed condition.

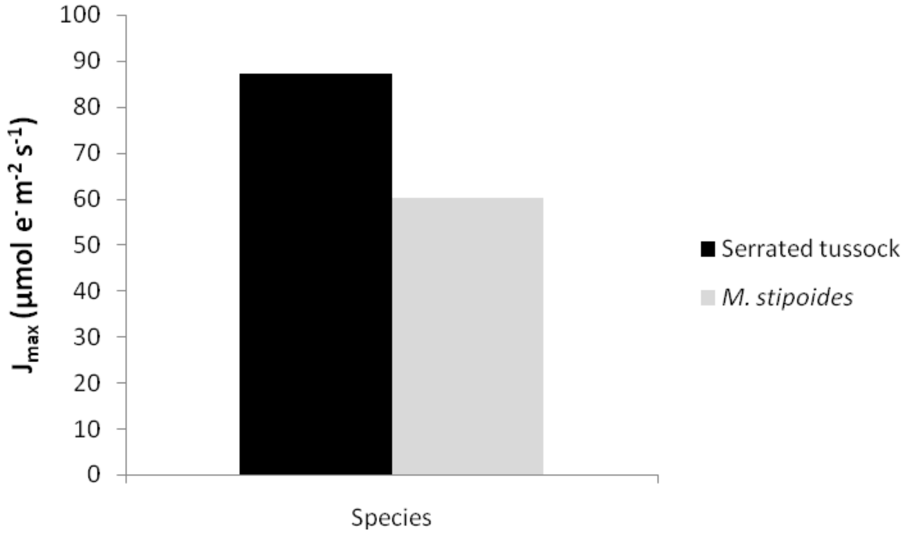


Figure 31. Mean maximum electron transport capacity of serrated tussock and *M. stipoides* grown in well watered and water stressed conditions.

Little has been done on the physiology of serrated tussock to resolve all the mechanisms it uses to maintain a dominant position in many landscapes and these results suggest:

- that serrated tussock has the potential to produce more photosynthate than *M. stipoides* under low or high moisture conditions
- serrated tussock may maintain higher reserves which enables the plant to survive adverse seasons and respond to improved conditions more readily
- once established serrated tussock will have the competitive advantage over native grasses such as *M. stipoides* in wet and dry years

4.3 Extension deliverables produced by the project

4.3.1 Field days

The results from this project were extended to farmers at a final series of field days during May 2009 in key serrated tussock areas of Kerr's Creek north of Orange, Trunkey Creek south of Bathurst, Middle Arm north of Goulburn and Nimmitabel south of Cooma. More than 200 farmers attended the field days that were run in conjunction with the NSW/ACT Serrated Tussock Working Party, landholders and the respective NSW DPI local district agronomist. Attendees were landholders, CMA representatives and council weeds inspectors. Those that provided their contact details will be posted a copy of the extension materials produced by the project (outlined in points 4.4.2 and 4.4.3).

Dr Simmons participated in other field days during the course of the project. These were: a field day organised by the Upper Macquarie County Council at Bathurst during March 2007

(60 attendees); another at Braidwood during November 2008 (50 attendees) and Trunkey Creek during July 2008 (11 attendees). Dr Simmons also presented findings from this project at the 14th Biennial NSW Weeds Conference to weeds inspectors from nearly every council in NSW.

Findings from this project have been disseminated to farmers through several articles in ProGrazier and Feedback magazines and on interviews with local ABC radio.

Dr Simmons presented findings from this project at the 5th International Weed Science Congress and joint International Rangelands Congress/International Grasslands Congress and was awarded an AW Howard Memorial Trust travelling fellowship towards the costs of attending these congresses.

4.3.2 Economic model – Serrated tussock: Estimating benefits of control in native and natural pastures

Results from this project were used to produce an economic modelling tool that estimates the impacts of potential control scenarios on production. Every paddock that contains or is threatened by serrated tussock is different so the purpose of the tool is to provide farmers with an estimate of their livestock production and net financial returns under different control scenarios over a 10 year period that they can use to base their management decisions on. A copy of the model and accompanying instruction booklet are attached to this report. The economic tool was developed in conjunction with a NSW DPI economist and showcased to over 200 serrated tussock affected landholders. Feedback from these landholders indicated that the tool will be extremely useful in determining the best strategies for control of serrated tussock on their properties. The most interest was from farmers in the Goulburn area; farmers in the low productivity Trunkey Creek area were less enthusiastic.

4.3.3 Deliberation tool – Serrated tussock: Getting the basics right

Results from other research done in conjunction with this project highlighted that existing extension materials were overloaded with information that made it difficult for farmers to understand and implement serrated tussock control strategies (see section 4.4), particularly those who seemed to find difficulty in starting to control this weed until they got a noxious weed notice. This identified a need for extension materials that provided the basics of serrated tussock control in a simple to understand manner and materials that assisted farmers in choosing the best control methods for their paddocks. To fill this need, a deliberation tool "*Serrated tussock: Getting the basics right*" was developed. This tool was developed in conjunction with NSW DPI district and research agronomists, serrated tussock affected farmers and serrated tussock researchers. A copy of the tool is attached to this report.

4.3.4 Serrated Tussock Best Management Practice Manual

The Victorian DPI funded the production of an updated best management practice (BMP) manual for serrated tussock. Dr Simmons collaborated with consultants, employees of NSW and Victorian DPI's and the national serrated tussock co-ordinator, Bronwen Wicks, as a technical editor to provide technical expertise on control of serrated tussock in native pastures. An electronic version of the manual can be found at on the internet at;

http://www.weeds.org.au/WoNS/serratedtussock/docs/stbpmmi.pdf

4.3.5 Distribution plan

The tools *Serrated tussock: Getting the basics right* and *Serrated tussock: Estimating the benefits of control in native and natural pastures* will be distributed through the NSW Department of Primary Industries bookshop with copies of the Serrated Tussock Best Management Practice manual and will also be available online from the www.weeds.org.au website. The national serrated tussock co-ordinator will ensure that these tools are promoted through press releases and news items on a regular basis. Research (outlined in section 4.4) suggests that farmers with the perception that serrated tussock cannot be managed will need assistance to understand information on serrated tussock control that is provided to them. The NSW DPI bookshop distributes extension materials to councils on a regular basis and weeds inspectors can provide the necessary assistance to landholders so these tools are used effectively. The need for more assistance for landholders to understand and implement serrated tussock control best practices has been recognised by councils (*e.g.* Upper Macquarie Country, Upper Lachlan Shire, Goulburn-Mulwaree Council) and the Upper Lachlan Shore Council is currently setting up a community group, in conjunction with a local Landcare group, to tackle the local serrated tussock problem.

4.3.6 Scientific papers

Results from the extensive Trunkey Creek field experiment will be submitted to refereed journals. Quality ecological data was collected through a difficult series of years so rather than produce manuscripts on only those conditions, data collection continued to the conclusion of the project to better understand the impacts of treatments in years when rainfall was closer to the average. That additional data will take some time to analyse, but preliminary evaluations suggest that the recommendations in this report will not be changed. These publications will be prepared during late 2009.

A manuscript based on the results from the allelopathy experiment has been produced and is ready for submission. Results from the other small scale experiments will probably not be published individually at this stage as they were preliminary, but the main points will be included in other relevant papers. Additional work on the physiology of serrated tussock in the field does need to be done and the small components presented in this report would be relevant for inclusion in more comprehensive studies.

4.4 Integration with other work on serrated tussock

Integration of this project with other work on serrated tussock carried out by the NSW/ACT serrated tussock working party, the national serrated tussock taskforce, county council weeds inspectors and employees of NSW and Victorian DPI's has been outlined above in sections 4.3.1, 4.3.2, 4.3.3 and 4.3.4. Working with council weeds inspectors and employees of NSW DPI (particularly district agronomists) meant research that was done was developed to fulfil needs of people who are involved in on-ground management of serrated tussock. Research on the social aspects of serrated tussock control was also done by the research team in parallel to the MLA funded work. Funding from the Defeating the Weeds Menace (DWM) program and Australia Wool Innovations (AWI) was combined to support the social research. The results from the research done using the additional funding guided the development of the extension tools prepared by this project.

Key results from the studies funded by DWM and AWI suggest that farmers with a high density of serrated tussock on their farm can be characterised into 3 distinct groups. The first group is distinguished by:

- a perception that serrated tussock could not be managed
- an absence of information and understanding on serrated tussock control principles (*e.g.* non-target effects of herbicides, mechanisms of invasion especially disturbance and the benefit of changing management practices (*e.g.* resting paddocks)
- reactive rather than proactive management approach
- a propensity to view their properties as 'rough' and marginal

The second group was distinguished by:

- a perception that serrated tussock could be managed
- recognition that current management practices were inadequate to keep serrated tussock in check and were actively changing their management practices to achieve this goal

The third group was distinguished by:

- a perception that the density of serrated tussock on their property was declining or already at minimal levels
- a proactive approach to serrated tussock control
- a clear understanding of grazing management practices

It is suggested that farmers in group 1 would require significant intervention and significant external resources to implement effective serrated tussock management. They would likely require an initial period of one-on-one interaction with extension officers to interpret extension materials and understand how to implement them, with subsequent follow-up visits to troubleshoot any problems that occur. The absence of an understanding of serrated tussock control principles by these farmers highlighted the need for extension materials that stepped farmers through the decision making process and demonstrated the benefits of changing paddock management. This need has been fulfilled through the production of the tools - *Serrated Tussock: Getting the basics right* and *Serrated Tussock: Estimating benefits of control in native and natural pastures.*

5 Success in Achieving Objectives

- develop management practices to significantly limit the recruitment of serrated tussock seedlings within serrated tussock infested native grasslands.

The key principle to limit recruitment devised by this project is that in drier years bare ground on lower slopes must be kept to less than 80%. Data collected from the Trunkey Creek experiment shows that the constantly grazed plots had the greatest bare ground; the least acceptable grazing management practice. For the herbicide treatment, bare ground was greatest in the fluproponate treatment, hence this is the least acceptable method of applying herbicide. On upper slopes, serrated tussock is very unlikely to establish in dry years when stocking rates are lower than currently practiced and moderate levels (~1.5 t DM ha^{-1}) of desirable perennial grass species are maintained.

- develop rules for managing serrated tussock infested grasslands for upper and mid-lower slope communities where the native perennial grass species and site productivity differs.

Results from the project suggest that upper and lower slopes respond differently to management however a margin of error needs to be built into any rules. This margin of error allows the principles of managing upper and lower slopes to be combined and makes implementation of the rules easier for managers. The upper and lower slopes effectively represent a significant part of the range in environments where serrated tussock grows.

Grazing management

Rule 1 – Retain greater than 1.5 t ha^{-1} of perennial grass herbage mass at all times of the year to ensure adequate competition against serrated tussock seedlings.

Rule 2 – Maintain a ratio of perennial grass : serrated tussock of greater than 5:1 to provide competition against adult serrated tussock plants.

Rule 3 – Follow guidelines developed by the pasture recruitment project (MLA PAST.125) to ensure perennial grasses recruit. Those recommendations are not in conflict with the better management practices recommended here.

Herbicide use

Rule 4 – If a pasture is dominated by C4 grasses, apply broadacre glyphosate in winter.

Rule 5 – If a pasture is dominated by C3 species, apply broadacre glyphosate in summer.

Rule 6 – If a pasture is dominated by any grass other than red grass (*Bothriochloa macra*) or kangaroo grass (*Themeda australis*) and broadacre fluproponate is applied then the paddock must remain ungrazed until adequate perennial grass herbage mass (see rules 1 and 2) is present.

- determine the efficacy of novel management methods based on manipulating herbage mass, litter and soil nutrient levels to reduce the competitiveness of adult serrated tussock plants.

Experiments that were done to examine novel methods of weakening serrated tussock did not develop any successful new techniques to weaken or reduce the competitiveness of serrated tussock plants.

- develop operational links with the Serrated Tussock Taskforce.

Operational links with the serrated tussock taskforce were present throughout the project. Dr Simmons assisted the taskforce with serrated tussock management plans, annual reports on serrated tussock research, the *Serrated Tussock National Best Management Practice Manual* and field days run in conjunction with the NSW/ACT serrated tussock working party.

- publish extension material on recommendations on outcomes from the project and holding at least four field days for producers and advisors to demonstrate control principles.

The project developed two extension tools; *Serrated tussock: Getting the basics right* and *Serrated tussock: Estimating the benefits of control in native and naturalised pastures.* Four key field days, attended by 200 people, were held at the conclusion of the project at Kerr's Creek north of Orange, Trunkey Creek south of Bathurst, Middle Arm north of Goulburn and Nimmitabel south of Cooma. Field days were a combination of disseminating results from research, demonstrating the extension tools and practical on-ground explanations of control techniques (*i.e.* herbicide application, determining density of serrated tussock infestation, identification of native grasses and discussing susceptibility and/or tolerance to herbicides).

6 Impact on Meat and Livestock Industry – now & in five years time

The experiments in this study have provided farmers with the information they need to maintain the competitiveness of their pastures and reduce serrated tussock invasion. A reduction in seedling invasion means lower control costs that can offset income losses due to lower production[1]. This project provided a better understanding of how management of the grazing of neighbouring desirable species can either lessen the impact of or provide serrated tussock with, a competitive advantage and the potential negative impacts of chemicals in serrated tussock foliage and roots on native grass growth and development. The simple to use and interpret tools developed by this project are providing farmers that struggle to develop useful serrated tussock control plans from the swathes of available extension materials with the means to better understand how to implement best management practices and to compare the economic benefits of their current practices to the new recommended best management practices presented in this report. The dissemination of these tools and the extension of information assembled by this project by extension officers will provide farmers with a rationale to tackle the problem of serrated tussock in a more pro-active fashion and run a more profitable enterprise.

7 Conclusions and Recommendations

Serrated tussock can be controlled, but it takes 3D's: diligence, deliberation and (minimal) disturbance. Problems from disturbance were known but the results in this project show that the best predictors of serrated tussock levels in a pasture are the various measures of disturbance used which provided more specific criteria (*e.g.* proportion of bare ground and invasion of broadleaf weeds) than were previously available. The reverse of minimising niches where serrated tussock seedlings can establish and of maintaining a competitive sward of desirable perennial grasses is then the initial requirement to prevent survival of serrated tussock seedlings and to halt the growth of existing serrated tussock adult plants. Effective management of a property threatened or infested with serrated tussock requires:

The re-assessment of farm management

Stock type and management need to be considered and this may be relatively simple changes such as reducing mob numbers by combining mobs, or fencing areas off to create more paddocks, to more complex changes such as changing an enterprise from fine wool to fat lambs.

Farm hygiene practices need to be implemented to minimise distribution of seed between paddocks.

[1] In resolving the economics of the new management strategies for serrated tussock control coming from this project there is a real problem of what to compare it against. Conventionally the 'control' in such circumstances is the current or historic stocking rates. However those rates are arguably too high and unrealistic in terms of a sustainable stocking rate. Current and historic rates have lead in part, to the decline in productivity observed and to invasion by serrated tussock. Sustainable stocking rates will differ for individual circumstances (*e.g.* climate, soil type, pasture type) and is best determined as that which allows herbage mass of perennial grasses to be maintained at recommended levels.

- Run purchased stock in a holding paddock for several days to ensure any seed they may have in their digestive system, or in wool or hair, is deposited in the holding paddock and not the productive pastures.
- Feed stock in a sacrifice paddock. This will stop any seed in imported fodder from dispersing through the farm and will also mean there is only one paddock that will be a high risk from invasion because of low herbage mass once feeding has ended.

Active grazing management

Exclude grazing and rest paddocks when;

The herbage mass of desirable perennial grasses falls below 1.5 t DM ha^{-1} to outcompete serrated tussock seedlings.

This herbage mass of perennial grasses is essential over the summer period however it is suggested that farmers aim to maintain this level during all seasons. One reasoning behind this is that farmers may not have the capacity to manage a paddock so that the herbage mass taken below this point in less critical times then allowed to accumulate so that 1.5 t DM ha^{-1} is present at all times of the year. The other is that seasonal variability may mean that farmers reduce their herbage mass below this point over winter with the intention of increasing herbage mass to 1.5 t DM ha^{-1} for the summer period only to have a dry spell set in and keep growth, and herbage mass, below this point.

Desirable grass species are flowering and setting seed to allow recruitment of desirable species.

Timing of rests will be dependent on the season and species of perennial grasses. To successfully initiate recruitment farmers need to;

- identify the grasses in the paddock that are desirable

- remove stock when the seedheads appear on the desirable grasses

- identify when seed has dropped from the seedhead (*ie.* by picking a seedhead and determining the presence or absence of seeds)

- stock can be moved onto paddock when seeds are absent from the seedhead (*ie.* seeds have fallen from the seedhead).

Maintain a PG:ST ratio of > 5:1.

Perennial grasses reach maximum competitiveness when the PG:ST ratio is > 5:1 so this ratio should also be aimed for. It is recommended that a series of photo standards be produced to demonstrate the 5:1 ratio of perennial grasses: serrated tussock under different conditions (*e.g.* serrated tussock sizes, perennial grass types).

These grazing rules need to be followed in any paddock susceptible to serrated tussock invasion regardless of the density of the serrated tussock infestation as they limit serrated tussock spread and growth.

Deliberative use of herbicides

Although the grazing rules apply for any paddock that is threatened by serrated tussock invasion, tactics for herbicide application are dependent on serrated tussock density. To use herbicides effectively:

- Priority should be given to ensuring that serrated tussock densities in paddocks that are clean, or only have a light infestation of serrated tussock, are not allowed to increase. This is done by spot spraying any plant by October before it seeds.
- Herbicides should be used in a manner that does not cause disturbance (*i.e.* mortality of existing species that compete against serrated tussock).
- Learn to identify common native grasses in your paddocks and understand how the herbicide you choose to use and how you choose to use it will affect those grasses.

The options for management have been incorporated into a decision support tool *Serrated Tussock: Getting the basics right* with an accompanying spreadsheet model that enables farmers to trial options for serrated tussock management. This tool evaluates alternatives over a ten year period to highlight how a longer-term view brings better rewards. One reason this tool was developed, was to help those producers who in related sociological research have shown a reluctance to initiate control of serrated tussock (Farmer Groups 1 and 2 identified earlier; section 4.4). The goal is to provide a step by step strategy to simplify decision making. Linked to better weed management is the need to improve pasture management for livestock production and the tools developed in this project aim to complement those delivered in Prograze and Landscan courses.

This project has provided farmers with new quantifiable guidelines for the better management of serrated tussock than were previously available. These guidelines were developed mainly through drought years. Further work, on and off-farm is obviously needed to see if the criteria from this project where serrated tussock is kept in check (>1.5 t DM ha^{-1} and 5:1, perennial native grasses : serrated tussock herbage mass) apply in wetter seasons or other conditions. Dry years are though arguably a good opportunity to manage serrated tussock as the ability of serrated tussock seedlings to survive is greatly reduced. Differences between upper and lower slopes were evident in this project and other work (Hackney, *unpublished*) has suggested that paddocks be fenced to separate upper and lower slopes and north and south aspects because in general the considerable differences in pasture productivity and the factors driving that make it difficult, even in the absence of weeds, to adequately manage the landscape. Such strategy has much appeal in the context of managing serrated tussock. In addition though farm scale strategies need to be developed that accommodate the rest periods needed to limit serrated tussock seedling recruitment while providing enough forage elsewhere on the farm to sustain the animal numbers that could be carried. Our discussions with farmers indicate they are uncertain how to change their livestock and paddock management practices to achieve income and landscape improvements. Serrated tussock management needs to move on from being seen as simply a weed issue to a serious weed that needs to be managed within the farm context while endeavouring to optimise the livestock enterprise. Future research needs to incorporate such a philosophy.

Transferability of recommendations

The recommendations made in this report are applicable to all native pastures that are threatened, or invaded, by serrated tussock. The effects of herbicides on perennial grasses will not vary between regions because the susceptibility of a species to a particular herbicide is dependent on physiology only. The parameters set for grazing management in the pasture matrix (*i.e.* maintain 1.5 t perennial grass DM ha^{-1} at all times of the year and a 5:1 PG:ST herbage mass ratio) are transferable for a number of reasons. As was demonstrated by the graph showing the relationship between serrated tussock growth and the PG:ST herbage mass ratio a reasonable margin of error has been allowed for in making the recommendation (*i.e.* the benefit of a 2:1 PG:ST ratio compared with a PG:ST ratio of 5:1 was arguably minimal). Further, the recommendation has been developed from data recorded on upper and lower slopes. These slopes represent different growing environments in Trunkey Creek but they also represent soil properties, water relations and climatic conditions of other localities. By analysing data from both upper and lower slopes as one dataset the recommendation effectively covers a range of growing conditions.

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9 Appendices

9.1 Appendix 1 – Draft allelopathy paper

Allelopathic effects of *Nassella trichotoma* on *Microlaena stipoides* and *Chloris truncata*

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Abstract

Nassella trichotoma is an unpalatable grass weed that is particularly problematic in native pastures and grasslands in the temperate regions of Australia. It is currently unknown whether the presence of *N. trichotoma* affects native grass species. This study investigated the effects of *N. trichotoma* leaves and roots on the germination and growth of *Microlaena stipoides* and *Chloris truncata.* Teas made from leaves of *N. trichotoma* (10% w/v) and roots (5% w/v and 10% w/v) resulted in germination of both species to lag behind the control but there was no significant difference in germination at the conclusion of the experiment. A pot experiment was used to determine whether the presence of *N. trichotoma* litter influenced the growth of *M. stipoides* and *C. truncata.* The presence of 500 kg ha^{-1} of litter reduced the above-ground biomass of *C. truncata* compared to other treatments and the below-ground biomass of *C. truncata* was lower in treatments with 500 kg ha^{-1} than those with 4000 kg ha^{-1}. *M. stipoides,* however, was not affected by the presence of litter. This study suggests that the presence of *N. trichotoma* may influence some native grasses and these effects may need to be considered when planning management of native pastures and grasslands.

Introduction

Nassella trichotoma (Nees) Hack ex. Arechav (serrated tussock) is an unpalatable grass weed that invades temperate pastures. It has been estimated to cost producers in New South Wales, Australia, $40m per annum in lost production (Jones *et al.* 2006). *N. trichotoma* will invade pastures regardless of soil fertility or type (Healy 1945), however the weed is particularly difficult to control in native pastures due to their propensity to be on steep rocky ground with poor soil quality, attributes that make the sowing of more competitive species uneconomical (Vere *et al.* 1997)

Research by Badgery et al. (2008) suggests that competition from native perennial grasses is a useful tool for suppressing the establishment of *N. trichotoma* seedlings in native pastures. Degraded native pastures have a low perennial grass content so may not produce adequate perennial biomass to outcompete *N. trichotoma* seedlings trying to establish during summer, the season they are most vulnerable (Badgery *et al.* 2008). One method of rejuvenation for degraded pastures is to increase the seedbank by resting pastures at key times so that native perennial grasses set seed (Bellotti and Moore 1994) that subsequently germinates and establishes leading to an increase in perennial grass content and, hence, more competitive pastures.

A number of requirements (*e.g.* moisture, light, nutrients) are needed for a seed to germinate and then successfully establish itself. Other factors, however, may also play a role in the successful establishment of pasture species. Previous research has demonstrated that the presence of leaf parts can affect the germination of grasses. Emeterio et al. (2004) reported that aqueous extracts prepared from *Lolium rigidum* leaves reduced the germination of *Lolium multiflorum* and *Dactylis glomerata* and the germination of *Triticum aestivum* was reduced by exposure to aqueous extracts prepared from *Galium aparine* (Aziz *et al.* 2008). The presence of leaf parts can also affect the growth of grasses. Aziz et al. (2008) reported that the root dry weight, shoot dry weight and biomass of *Triticum aestivum* were also significantly reduced by aqueous extracts prepared from *Galium aparine.*

The presence of roots may also affect the germination and growth of grasses. Bais et al. (2002) reported that the application of root exudates from *Centaurea maculosa* resulted in death of *Bromus tectorum,* and *Triticum aestivum* seedlings 14 days after application. The presence of exudates also reduced the germination of *B. tectorum* and *T. aestivum*. In contrast, Emeterio et al. (2004) reported that aqueous extracts from *Lolium rigidum* roots enhanced the germination of *Lolium multiflorum* at low concentrations and that high and low concentrations increased the length of coleoptiles and radicles of *L. multiflorum* and *Dactylis glomerata*.

N. trichotoma produces copious amounts of senescent leaf material and has a relatively large and fibrous root system yet it is unknown how the presence of these plant parts chemically influence the growth and germination of grasses in native pastures and grasslands. Accordingly, this study was designed to determine whether; the presence of *N. trichotoma* roots and leaves may affect the germination of two grass species found in native pastures, *Microlaena stipoides* (Labill.) R.Br. and *Chloris truncata* R.Br and; the presence of

N. trichotoma litter may affect the above- and below-ground growth, and morphological characteristics, of these two species.

Materials and Methods

Experiment 1

Methods were derived from Halsall et al. (1995).

Plant material

Whole *N. trichotoma* plants were collected from the field, air dried and stored in a cool, dry and dark environment until required. Seeds of *M. stipoides* and *C. truncata* were acquired from Native Seeds Pty. Ltd., Cheltenham, Australia and were stored in a cool, dry and dark environment until required.

Experimental design

A two-way factorial randomised block design with five blocks was used. The first factor was species (*M. stipoides* and *C. truncata*) and the second was extract (control – sterile distilled water, 5% w/v of *N. trichotoma* leaf or root material, 10% w/v of *N. trichotoma* leaf or root material).

Methods

Extracts were made by placing 5 or 10 g of leaves or roots that had been cut into 5 mm long pieces in 100 ml of water in a specimen jar. The specimen jar was then shaken for 3 hours after which time jars were placed in the refrigerator for a further 12 hours. After this period jars were placed in a centrifuge after which the supernatant was carefully removed and filtered into sterile beakers using sterile filter paper under aseptic conditions. Seeds were surface sterilised by soaking in a solution of 2.7 % NaOH in sterile distilled water for 5 minutes then rinsed in sterile distilled water for five minutes four times to remove any residual NaOH. 20 seeds each of *M. stipoides* and *C. truncata* were placed in a 100 mm diameter plastic petri dish that had three sterile filter papers placed on the bottom. 3 ml of each tea was placed in the petri dish, the lid placed on top and sealed with parafilm. Petri dishes were placed in a cooling incubator at a 22/13ºC day/night temperature regime and under constant light. The numbers of germinated seeds were counted on a daily basis until no more seeds germinated.

Statistical analysis

Genstat (v. 11) (Genstat Committee 2008) was used for analysis. Data were homogenous so were not transformed. A two-way ANOVA was used to detect differences between species and extracts at each individual time point. Statistical significance between treatments was determined by the least significant differences test.

Experiment 2

Plant material

Plant material was used as described for experiment 1.

Experimental design

A two-way factorial randomised block design with four blocks was used. Numerous seeds of *M. stipoides* and *C. truncata* were sown in a large black plastic pot filled with potting mix placed in a shade house and watered every second day. Three weeks after germination, seedlings of similar size were transplanted into individual 10 cm diameter black plastic pots filled with potting mix and either 0, 0.15, 0.3 or 1.2 g of *N. trichotoma* litter (the equivalent of 0, 500, 1000 and 4000 kg litter ha^{-1}) cut into 5 mm lengths was placed on the soil surface. Pots were placed in randomised blocks in a glasshouse at 25 ± 6º C and watered daily. Four months after being transplanted the height of the most recently emerged leaf on the main tiller, numbers of leaves and tillers, and the width of the most recently expanded leaf on the main tiller were recorded. The above ground biomass was excised, dried at 60º C for four days and weighed. Roots were separated from the potting mix, dried at 60º C for four days and weighed. Samples were then ashed to estimate the amount of media remaining on the roots and root dry weights were corrected.

Statistical analysis

Prior to analysis all data was subjected to $\sqrt{x+0.5}$ transformation. Data was checked for outliers using a boxplot and one replicate removed. Differences between treatments for all variables were then analysed using the unbalanced ANOVA function in Genstat (v. 11) (Genstat Committee 2008). Statistical significance between treatments was determined by the least significant differences test.

Results

Experiment 1

The percentages of germinated seeds treated with aqueous extracts prepared from 5g roots, 10 g of leaves and 10 g roots were significantly less than the control on days 3 (P=0.40, $F_{(4,39)} = 2.92$) and 4 (P=0.39, $F_{(4,39)} = 2.92$). On day 3 the 5 g root, 10 g root and 10 g leaf treatments had 77, 74 and 75 % germination of the control, respectively (figure 2). On day 4 the 5 g root extract treatment had 79 %, the 10 g root extract 73 % and 10 g leaf extract 77 % germination of the control. The numbers of germinated seeds were significantly greater for *C. truncata* than for *M. stipoides* for all time points (P<0.001 d.f. and F, data not shown).

Experiment 2

The species x litter interaction was significant for above-ground biomass (P=0.009, $F_{(3,30)} = 5.03$) *C. truncata* grown with 4000 kg ha^{-1} of litter had the largest above-ground biomass and *C. truncata* with 1000 kg ha^{-1} and 0 kg ha^{-1} litter had the next largest. The above-ground biomass of *M. stipoides* was lower than *C. truncata* and did not differ between litter treatments (table 1). The species x litter interaction was also significant for below-ground biomass (P=0.041, $F_{(3,30)}$ = 3.32). *C. truncata* grown with 4000, 1000 kg ha^{-1} of litter had a greater below-ground biomass than *C. truncata* grown with 500 kg ha^{-1} but the below-ground biomass of *M. stipoides* did not differ between litter treatments.

C. truncata had a significantly greater plant height (P<0.001, $F_{(1,30)}$ = 36.48), leaf width (P<0.001, $F_{(1,30)}$ = 17.12), above-ground biomass P<0.001, $F_{(1,20)}$ = 42.46) and below-ground biomass (P<0.001, $F_{(1,30)}$ = 30.59), and significantly fewer tillers (P<0.001, $F_{(1,30)}$ = 45.15) and leaves (P<0.001, $F_{(1,30)}$ = 153.34) than *M. stipoides* (data not shown).

Discussion

This study is the first to show that *N. trichotoma* may contain allelopathic compounds and that these compounds may affect two grasses commonly found in Australian native pastures and grasslands that are prone to *N. trichotoma* invasion. Treatments consisting of aqueous solutions prepared from roots and leaves delayed the germination of both species tested. Similar delays in germination have been reported for *Triticum aestivum* exposed to *Vulpia myuros* residues (An *et al.* 1997) and for *L. multiflorum* and *D. glomerata* exposed to *L. rigidum* residues (Emeterio *et al.* 2004). The delay in germination, without subsequent inhibition of full germination, indicates that the aqueous extracts tested were mildly phytotoxic (An *et al.* 1997) in contrast to highly toxic extracts that have resulted in a 100 percent reduction in germination of other species (Leigh *et al.* 1995b). Further, extracts prepared from 5 g of root material significantly delayed germination whilst those prepared from 5 g of leaf material did not. This suggests that the concentration of allelopathic compounds may differ between roots and leaves as has been shown to occur in *Oryza sativa* (Kong *et al.* 2004) and *T. aestivum* (Wu *et al.* 2000).

The results from this study showing that relatively low amounts of *N. trichotoma* litter reduced the above-ground biomass of *C. truncata* relative to the control indicate that relatively small amounts of allelopathic compounds in leaves may have a negative influence on *C. truncata* seedlings. In contrast, when 4000 kg litter ha^{-1} were present the above-ground biomass of *C. truncata* was greater than the control. This increase may have been due to the litter acting as a mulch, (*i.e.* reducing the rate at which soil dries and retaining soil moisture), however the absence of any benefit to *M. stipoides* indicates that higher concentrations of compounds found in litter may have a stimulatory effect on *C. truncata,* similar to that reported for *L. rigidum* on *L. multiflorum* (Emeterio *et al.* 2004).

The present study found that 4000 kg of *N. trichotoma* litter ha^{-1} increased above-ground biomass by six percent. This amount of litter would, however, only be found in very dense infestations where the density of native perennial grasses is low. It is unlikely that any increases in biomass from the presence of this amount of litter would be of benefit to grasslands.

Current *N. trichotoma* management guidelines do not consider the effects that litter may have on neighbouring perennial grass species. Native perennial pastures often have

1000 kg of *N. trichotoma* litter ha^{-1} present and *N. trichotoma* plants that have been killed, by herbicide or mechanical removal, are left in the paddock. Considering that most allelopathic compounds have an effect on multiple species further work is required to determine the effect of allelopathic compounds on other native perennial grasses (e.g. *Austrodanthonia* spp., *Bothriochloa* spp. and *Elymus* spp.). Management recommendations of *N. trichotoma* infested native grasslands may then have to be modified to account for any allelopathic effects that exist.

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Figure 1. Mean percentage germination of *Chloris truncata* and *Microlaena stipoides* germinated in either water (control) or teas made with *N. trichotoma* leaf material (10% w/v) or roots (10% w/v and 5% w/v). * designates treatments that differed significantly (P=0.05) by the LSD. Data for treatments with 5% w/v leaves are not shown for clarity.

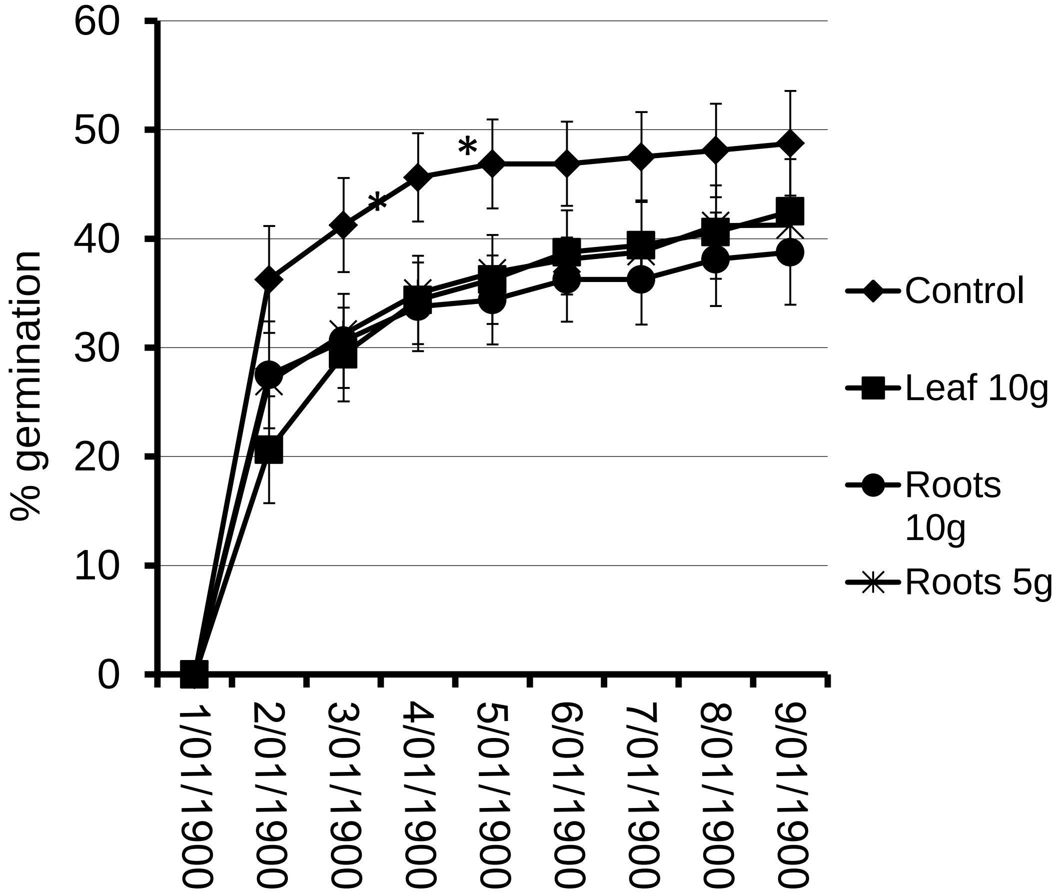

Table 1. Transformed √(*x* + 0.5) mean (± S.E.M.) height, numbers of leaves, leaf width, numbers of tillers, above- and below-ground biomass for *Chloris truncata* and *Microlaena stipoides* with 0, 500, 1000 or 4000 kg ha^{-1} of *N. trichotoma* leaf litter present. Means within columns followed by the same letter do not differ significantly by the LSD test (P=0.05).

Leaf litter ($kg\ ha^{-1}$)	**Species**	**Height (cm)**	**Leaves (no.)**	**Leaf width (cm)**	**Tillers (no.)**	**Above-ground biomass (g)**	**Below-ground biomass (g)**
0	*M. stipoides*	11.87 (± 0.608)	3.14 (± 0.156)	1.83 (± 0.089)	1.85 (± 0.156)	0.73c (± 0.002)	0.06bc (± 0.011)
	C. truncata	17.35 (± 1.861)	2.57 (± 0.174)	2.03 (± 0.205)	1.38 (± 0.162)	0.77b (± 0.023)	0.14ab (± 0.032)
500	*M. stipoides*	10.31 (± 1.307)	3.28 (± 0.368)	1.65 (± 0.072)	1.83 (± 0.211)	0.73c (± 0.012)	0.04c (± 0.010)
	C. truncata	14.08 (± 2.228)	2.43 (± 0.123)	1.80 (± 0.097)	1.28 (± 0.000)	0.73c (± 0.009)	0.07b (± 0.010)
1000	*M. stipoides*	11.96 (± 1.114)	3.19 (± 0.412)	1.90 (± .0.081)	1.92 (± 0.129)	0.73c (± 0.009)	0.04c (± 0.005)
	C. truncata	17.98 (± 1.190)	2.48 (± 0.131)	2.17 (± 0.060)	1.22 (± 0.000)	0.77b (± 0.008)	0.19a (± 0.024)
4000	*M. stipoides*	11.16 (± 0.726)	3.35 (± 0.282)	1.72 (± 0.084)	1.99 (± 0.072)	0.73c (± 0.004)	0.03c (± 0.004)
	C. truncata	18.49 (± 2.132)	2.72 (± 0.106)	2.23 (± 0.065)	1.47 (± 0.156)	0.82a (± 0.013)	0.21a (± 0.026)