

## Studies of competition between *Nassella trichotoma* (Nees) Hack. ex Arechav. (serrated tussock) and native pastures. 2. Seedling responses

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**Abstract.** Native perennial grass competition can substantially reduce the invasion of *Nassella trichotoma* (serrated tussock), a major perennial grass weed problem in south-eastern Australia. This paper reports on a field experiment that investigated the recruitment of *N. trichotoma* seedlings, and determined what level of native grass competition was needed to prevent establishment in the central-west of NSW. Grasslands that maintained >2 t dry matter (DM)/ha and 100% ground cover (measured in spring) prevented *N. trichotoma* seedling recruitment. Relatively small amounts of perennial grass (>0.5 t DM/ha measured in spring) resulted in mortality of *N. trichotoma* seedlings that had recruited earlier in the year, through the next summer. Flupropanate also markedly reduced native perennial grasses and substantially increased *N. trichotoma* seedling establishment 12 months after application. Rotational grazing to maintain adequate levels of DM was an important management tactic that prevented *N. trichotoma* establishment and survival.

**Additional keywords:** pasture competition, integrated weed management, flupropanate, grazing management, seedling establishment, seedling mortality.

### Introduction

*Nassella trichotoma* (Nees) Hack. ex Arechav. (serrated tussock) is the most serious perennial grass weed in south-eastern Australia. While its invasion is not strongly associated with rainfall, soil, or pasture type (Campbell and Vere 1995), invasion does not occur unabated across the landscape and managing the level of plant competition could have an important role in determining its invasiveness. Heaviest infestations are usually found in steep areas, with soils of low productivity. In these areas, it is inappropriate (Johnston 1996) or uneconomic (Jones *et al.* 2000) to sow vigorous *Phalaris aquatica* L.-based pastures to compete with *N. trichotoma* and prevent or limit invasion (Campbell 1960). Many of these areas still have a reasonable proportion of perennial native grasses (both C<sub>3</sub> and C<sub>4</sub> species) that are often heavily grazed and so in relatively poor condition and it is unclear whether these pastures could be better managed to prevent *N. trichotoma* invasion.

Adult *N. trichotoma* plants produce extremely large numbers of seed (averaging 16 600 seeds per plant in 2001 and 8800 seeds per plant in 2002 at the Trunkey site; Badgery *et al.* 2008) that can be dispersed up to 16 km by wind (Healy 1945), making it difficult to limit the incursion of *N. trichotoma* from neighbouring infestations. Rather than merely trying to prevent *N. trichotoma* seeds from reaching an area, managing the landscape to become more resistant to invasion may be a key strategy. The first step in formulating such a process is to define the conditions under which *N. trichotoma* seedlings establish and grow to reproductive maturity. Once these conditions are known

it may then be possible to devise management strategies as part of an integrated weed-management (IWM) package to limit their occurrence.

Most *N. trichotoma* seedling recruitment in south-eastern Australia occurs under moist, cool conditions (Healy 1945; Talyor 1987) that typically occur in the cooler months of the year. Seeds are more likely to germinate in autumn when large areas of bare ground are more common than in spring (Talyor 1987). Under favourable conditions, established *N. trichotoma* populations can produce a large number of seedlings, with densities up to 4000/m<sup>2</sup> (Campbell 1977). Mortality rate is high at this stage, however, because seedlings are small and have relatively low growth rates (Talyor 1987). Understanding when and where seedlings survive may assist in identifying both the conditions and management strategies required to limit invasion.

There is little information available on the microsite soil surface conditions that *N. trichotoma* seedlings need to establish and survive. Anecdotal evidence suggested that bare soil and disturbed conditions are favoured, but there are few data to confirm this (Michalk *et al.* 1999). Disturbance may be an important requirement for *N. trichotoma* establishment, because it reduces the density and vigour of other species, especially perennial grasses. Pasture-management strategies that limit disturbance may help native grasses to compete with establishing *N. trichotoma* seedlings and so diminish invasion rates. Previously, Badgery *et al.* (2005) demonstrated that native grasses effectively competed with *N. trichotoma*

seedlings in a pot experiment, particularly at lower soil fertility levels. In the field, *N. trichotoma* is rarely found growing among dense stands of native perennial grasses, especially the C<sub>4</sub> (summer-growing) *Themeda australis* (R.Br) Stapf and *Bothriochloa macra* (Steud.) S.T. Blake (Hocking 1998; Michalk *et al.* 1999; Badgery *et al.* 2001).

This paper reports on an experiment designed to determine how different grazing regimes (designed to vary the level of native grass competition), soil fertility, and *N. trichotoma* seed densities affected pasture and soil conditions and the germination and establishment of *N. trichotoma* seedlings.

## Methods

### Site

The experiment was located at Trunkey Creek on the Central Tablelands of New South Wales (NSW) (33.83°S, 149.35°E; see Badgery *et al.* (2008) for a complete site description). The experiment started in spring 2001 and continued until summer 2004. The site contained both C<sub>4</sub> (*T. australis* and *B. macra*) and C<sub>3</sub> (*Microlaena stipoides* (Labill.) R.Br and *Austroanthonia* spp. H.P. Linder) native perennial grasses.

### Design

The experimental design was a factorial combination of 2 grazing × 2 fertility × 3 seed manipulation treatments in a split-plot design, with 3 replicates in blocks. Plots layout ensured that C<sub>3</sub> and C<sub>4</sub> native grasses were included as well as *N. trichotoma*, and rocky or anomalous areas were avoided.

The 2 grazing treatments were continuous (G<sub>con</sub>) and active (G<sub>act</sub>) grazing, applied in 20 by 10 m plots using an open communal grazing design (Kemp and Dowling 2000). The G<sub>con</sub> treatment was continually grazed at a rate of 3–4 DSE (dry sheep equivalents)/ha throughout the experiment; the stocking rate being set by the cooperating farm manager for the larger paddock within which this experiment was located. The G<sub>act</sub> treatment was a rotational grazing treatment from the beginning of the experiment until January 2003 when it was changed to a summer rest for the duration. During the rotational grazing period, plots were grazed at 200 DSE/ha for 3 days twice a year (equivalent to 3 DSE/ha annually). Grazing commenced in the G<sub>act</sub> treatment when edible biomass (above-ground standing plant herbage excluding *N. trichotoma*) reached ~2 t/ha and was continued until biomass was reduced to ~1 t/ha. To benefit C<sub>4</sub> native species no grazing was imposed to the G<sub>act</sub> in the summer. The summer rest, when applied, extended from early January through until March each year before the paddock was opened to the same grazing pressure as the G<sub>con</sub> treatment.

Nested within the grazing treatments were 2 fertiliser treatments, nil (N<sub>nil</sub>) and increased fertility (N<sub>add</sub>), which were applied in 20 by 3.3 m plots. Fertiliser was not applied in the N<sub>nil</sub> treatment, whereas the N<sub>add</sub> treatment had the equivalent of 120 kg nitrogen (N)/ha, 30 kg phosphorus (P)/ha, and 18 kg sulfur (S)/ha applied each year in the form of 250 kg/ha of Granulock<sup>®</sup> 15 (N: 15, P: 12, S: 7) plus 170 kg/ha of urea (N: 48), in 4 seasonal applications.

Seed manipulation treatments were established within fertiliser treatment plots and comprised 3 levels: *N. trichotoma* seed addition (S<sub>add</sub>), nil (S<sub>nil</sub>), and herbicide (HE). A stratified random approach was used to allocate these

treatments, which were applied to single 4-m<sup>2</sup> areas that had *N. trichotoma*, and C<sub>4</sub> and C<sub>3</sub> native perennial grasses present. In the S<sub>add</sub> treatment, 50 000 *N. trichotoma* seeds/m<sup>2</sup> were applied, which was the average amount of seed found in a dense *N. trichotoma* stand in 2001 at the site. Seed-heads were collected on 16 January 2001, weighed, and the seed in subsamples counted to determine seed yield per m<sup>2</sup>. Seed-heads were finely chopped using scissors so they would not blow away, with care not to damage seed, and were then added to the treatment on 11 April 2001. The S<sub>nil</sub> treatment was not modified in any way. The HE treatment had 1.49 kg a.i./ha of flupropanate applied with a hand-held pneumatic sprayer on 17 April 2001. This treatment was designed to remove adult and seedling *N. trichotoma* plants, with the residual effect of the herbicide expected to control seed germination for up to 18 months and so was, in part, designed to examine whether the disturbance created by herbicide application had any effect on seedling recruitment.

### Measurements

*Nassella trichotoma* seedlings were assessed in a 250 by 250 mm permanent quadrats near the centre of each 4-m<sup>2</sup> plot (subdivided into 50 by 50 mm squares to aid mapping) to determine seedling recruitment (natality) and mortality from October 2001 to January 2003 at 3-month intervals. In February 2004, quadrats were sampled for final seedling counts and seedlings were divided into 3 size classes (those with <3, 3–10, and >10 mm basal diameter). Each quadrat was located at least 100 mm from an adult *N. trichotoma* plant and aligned within the centre of a quadrat of 9 squares (100 by 100 mm) in which covariates such as pasture biomass, species composition, bare ground, and litter were determined in spring 2002. Pasture biomass and species composition were estimated using BOTANAL techniques (Tothill *et al.* 1992). Dry weight ranks of the 3 most abundant species, as well as estimates of bare ground, litter, and the total dry weight of all species, were estimated for each 100 by 100 mm square and averaged for each quadrat. Dry weight estimates were corrected using 10 calibration cuts per sampling.

Seedlings were considered to be any *N. trichotoma* plant that had a basal diameter <40 mm (generally less than 18 months old, although some plants that were present at the initial measurement may have been older than this by the end of the experiment). Counts were taken in the middle month of each season (e.g. summer counts in January), so any new seedlings were recorded as having germinated in that season, even though they may have germinated at the end of the previous season.

Climatic data were recorded at the site (see Badgery *et al.* 2008) and used in the SGS Pasture Model (Johnson *et al.* 2003) to estimate the volumetric soil moisture content for the 0–20 mm soil depth for the duration of the experiment.

### Analyses

All analyses were performed using GENSTAT (version 6) (Payne *et al.* 2006). Analyses of variance (ANOVA) were done on the total number of seedlings at each sampling date and also on percentage of seedling survival. Seedlings present at the start of the experiment were mapped to determine establishment, survival, and subsequent mortality of individual seedling cohorts. Since it was not possible to determine when

seedlings germinated for the first measurement in late 2001, only the results for germination and subsequent survival were reported for summer 2002 to summer 2003. In addition, an ANOVA was done on each seedling size class and the total number of seedlings for the February 2004 measurement. Data were transformed  $[\ln(n+1)]$  where required to normalise the data.

A multiple regression analysis, including the covariates that were measured within each quadrat (total biomass (DM), bare ground (%), total perennial biomass (TP DM), and litter biomass), was used to identify the conditions important for seedling numbers. In addition, species composition for each quadrat was summarised as the axis 1 scores from an ordination [principal coordinate analysis (PCO)] calculated using Bray–

Curtis similarities in CANOCO (ter Braak and Smilauer 1998) and included in the analysis. A Pearson correlation coefficient matrix was used with Bonferroni correction of probabilities to determine the relationship among covariates.

## Results

### *N. trichotoma* seedling densities

Generally, *N. trichotoma* seedling densities (i.e. the sum of all germinating cohorts minus mortality) were at a maximum in autumn, winter, and spring and at a minimum in summer (Table 1). This pattern was reasonably consistent across all treatments and few seedlings were evident in summer when mortality was generally higher. Seasonal differences in total seedling density

**Table 1.** *Nassella trichotoma* seedling density ( $m^2$ ) for grazing, fertility, and seed manipulation treatments measured in each season  
Least significant differences (l.s.d.) are presented for significant interactions ( $P \leq 0.05$ ). Grazing  $\times$  fertility interactions were not significant and are not presented. n.s., not significant

Grazing	Treatments		Season					
	Fertility	Seed	Sp01	Su02	Au02	Wi02	Sp02	Su03
$G_{con}$			506	38	452	636	519	68
$G_{act}$			224	25	152	226	198	40
l.s.d. ( $P=0.05$ )			n.s.	n.s.	268.6	285.8	242.9	n.s.
	$N_{nil}$		458	34	377	453	372	30
		$N_{add}$		272	29	220	408	346
l.s.d. ( $P=0.05$ )			n.s.	n.s.	124.5	n.s.	n.s.	n.s.
		HE	72	19	481	765	597	137
		$S_{nil}$	348	43	172	291	284	21
		$S_{add}$	675	33	241	236	195	3
l.s.d. ( $P=0.05$ )			210.7	n.s.	n.s.	338.8	290.4	56.3
$G_{con}$		HE	69	5	571	912	667	155
		$S_{nil}$	499	61	317	547	509	43
		$S_{add}$	949	48	469	448	381	5
$G_{act}$		HE	75	32	470	619	528	120
		$S_{nil}$	197	24	27	35	59	0
		$S_{add}$	400	19	13	24	8	0
l.s.d. ( $P=0.05$ )			533	n.s.	n.s.	n.s.	n.s.	n.s.
except between the same level of grazing			298					
	$N_{nil}$	HE	93	29	536	667	464	72
		$S_{nil}$	547	48	253	379	395	13
		$S_{add}$	733	24	341	315	256	5
	$N_{add}$	HE	51	8	427	864	731	203
		$S_{nil}$	149	37	91	203	173	29
		$S_{add}$	616	43	141	157	133	0
l.s.d. ( $P=0.05$ )			n.s.	n.s.	n.s.	n.s.	n.s.	91.4
except between the same level of grazing								79.6
$G_{con}$	$N_{nil}$	HE	75	0	560	501	176	5
		$S_{nil}$	699	48	453	688	672	27
		$S_{add}$	949	48	656	587	501	11
	$N_{add}$	HE	64	11	581	1323	1157	304
		$S_{nil}$	283	59	165	389	331	42
		$S_{add}$	949	48	283	309	261	0
$G_{act}$	$N_{nil}$	HE	112	59	512	832	752	139
		$S_{nil}$	395	48	53	69	117	0
		$S_{add}$	517	0	27	43	11	0
	$N_{add}$	HE	37	5	272	405	304	101
		$S_{nil}$	0	0	0	0	0	0
		$S_{add}$	283	37	0	5	5	0
l.s.d. ( $P=0.05$ )			n.s.	n.s.	n.s.	n.s.	516.6	110.9
except between the same level of fertility							541.1	129.3
grazing $\times$ fertility							580.9	112.6
grazing $\times$ seed							541.1	129.3

across all treatments were associated with 0–20 mm soil water content (Fig. 1). Seedling numbers increased each year when estimated soil water content increased in early autumn, with total *N. trichotoma* seedling numbers peaking in mid-winter. Seedling density was lower ( $P < 0.001$ ) in summer, after or when soil water content was effectively at the predicted wilting point (11–12%) for protracted periods.

### Grazing

Initially, in spring 2001 or summer 2002, there was no difference in average *N. trichotoma* seedling densities among grazing treatments (Table 1). Overall, there was a large reduction in seedling number in summer 2002, but there was considerable variability among treatments and so no significant differences were detected. In autumn 2002, however, fewer seedlings were present in the  $G_{act}$  treatment than in the  $G_{con}$  treatments ( $P < 0.05$ ). This effect of grazing continued in winter 2002 ( $P < 0.05$ ) and the following spring ( $P < 0.05$ ), except in the  $G_{con}$ ,  $N_{nil}$ , HE treatments ( $P < 0.01$ ). In summer 2003 the  $G_{con}$  treatment still had more seedlings than  $G_{act}$  treatments, but the difference was not significant, partly because of the large reduction in overall seedling numbers (Table 1); however, the  $G_{con}$ ,  $N_{nil}$ , HE treatment was still lower than the other  $G_{con}$  treatments ( $P < 0.01$ ). No seedlings were present in the  $G_{act}$  treatment where no herbicide was applied.

### Fertility

Density of *N. trichotoma* seedlings was not significantly affected by fertility in spring 2001 and summer 2002, but in autumn 2002, the  $N_{add}$  treatment had fewer seedlings than the  $N_{nil}$  treatment ( $P < 0.05$ ), particularly with active grazing. However, after autumn 2002 there was no significant difference in seedling density between fertility treatments.

### Seed manipulation

In spring 2001, seedling density was highest in the  $S_{add}$  treatment, followed by the  $S_{nil}$  treatment, and lowest in the HE treatment ( $P < 0.001$ ). Within the  $S_{add}$  treatment, seedling density was higher ( $P < 0.05$ ) when continuous rather than active grazing

was imposed (Table 1). In summer and autumn 2002, there was no difference in seedling density among seed treatments, but by winter the HE treatment had significantly higher seedling numbers ( $P < 0.01$ ) and a similar pattern was evident in spring 2002 ( $P < 0.05$ ). However, in the HE treatment, fewer seedlings were recorded in the  $N_{nil}$  treatment under continuous grazing compared with active grazing, whereas in the  $N_{add}$  treatment the reverse was observed ( $P < 0.01$ ). In summer 2003, the HE treatment again had a higher seedling density ( $P < 0.001$ ) than the other seed manipulation treatments. Similar to the results for spring 2002, fewer seedlings were in the continuously grazed HE  $N_{nil}$  treatment, whereas more seedlings were recorded in the actively grazed HE  $N_{add}$  treatment ( $P < 0.05$ ).

### Germination and survival patterns

Both seedling germination and seedling survival regulated total seedling numbers, and varied markedly throughout the experiment (Table 1).

### Establishment

While establishment occurred in each season there were differences among treatments (Fig. 2), with no seedlings establishing in the  $G_{act}$   $N_{add}$   $S_{nil}$  treatment. There was more establishment in autumn and winter than in spring, with very few seedlings establishing in summer ( $P < 0.001$ ).

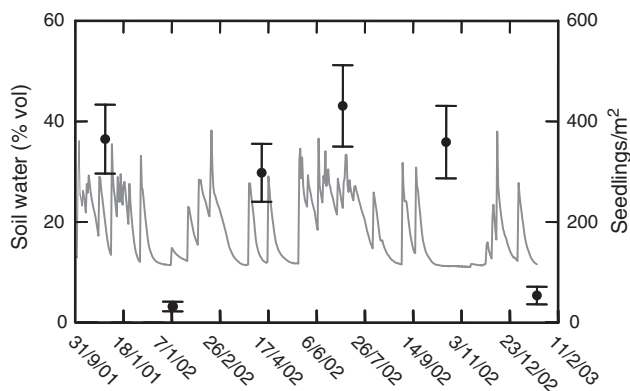
Throughout the experiment, more seedlings established in the  $G_{con}$  treatments than in the  $G_{act}$  treatments ( $P < 0.001$ ) and there were fewer seedlings where fertiliser was applied ( $P < 0.05$ ), mainly in actively grazed treatments ( $P < 0.05$ ). Seedling establishment was higher where herbicide was applied ( $P < 0.01$ ) and seedling numbers were lower in  $G_{act}$  treatments with no herbicide than in all of the  $G_{con}$  treatments and the  $G_{act}$  HE treatment ( $P < 0.05$ ).

Total number of seedlings establishing in each season varied with grazing treatments, and numbers in autumn, winter, or spring were not significantly different in the  $G_{act}$  treatment. In contrast, in the  $G_{con}$  treatment, more seedlings established in autumn and winter than in spring ( $P < 0.001$ ). More seedlings established in autumn and winter than in spring in the  $N_{nil}$  treatment, and in autumn, winter, and spring in the  $N_{add}$  treatment ( $P < 0.05$ ).

### Survival

Seedling mortality was high in all treatments, mostly occurring in summer 2002 and 2003 (Fig. 2).

In winter 2002, seedlings that established in autumn had a higher survival in the  $G_{con}$  treatment than in the  $G_{act}$  treatment ( $P < 0.05$ ). Seedling survival rate was higher in the HE treatment than in the  $S_{add}$  treatment, and higher in both these treatments than in the  $S_{nil}$  treatment ( $P < 0.001$ ). In the  $G_{act}$  treatments, seedlings had higher survival when herbicide was applied. Conversely, in  $G_{con}$  treatments, herbicide had no significant effect on seedling survival. In the  $N_{add}$  treatment, seedling survival was higher in the HE treatment than in the  $S_{add}$  treatment, which was higher than the  $S_{nil}$  treatment. However, in the  $N_{nil}$  treatment, survival was higher where herbicide was applied and there was no difference between the  $S_{add}$  and  $S_{nil}$  treatments ( $P < 0.001$ ).



**Fig. 1.** Soil water content (%/volume of soil, left y-axis) throughout the experiment as represented by the solid grey line and the average number of *N. trichotoma* seedlings/m<sup>2</sup> in all treatments (right y-axis, points), measured every 3 months, with standard error bars displayed.



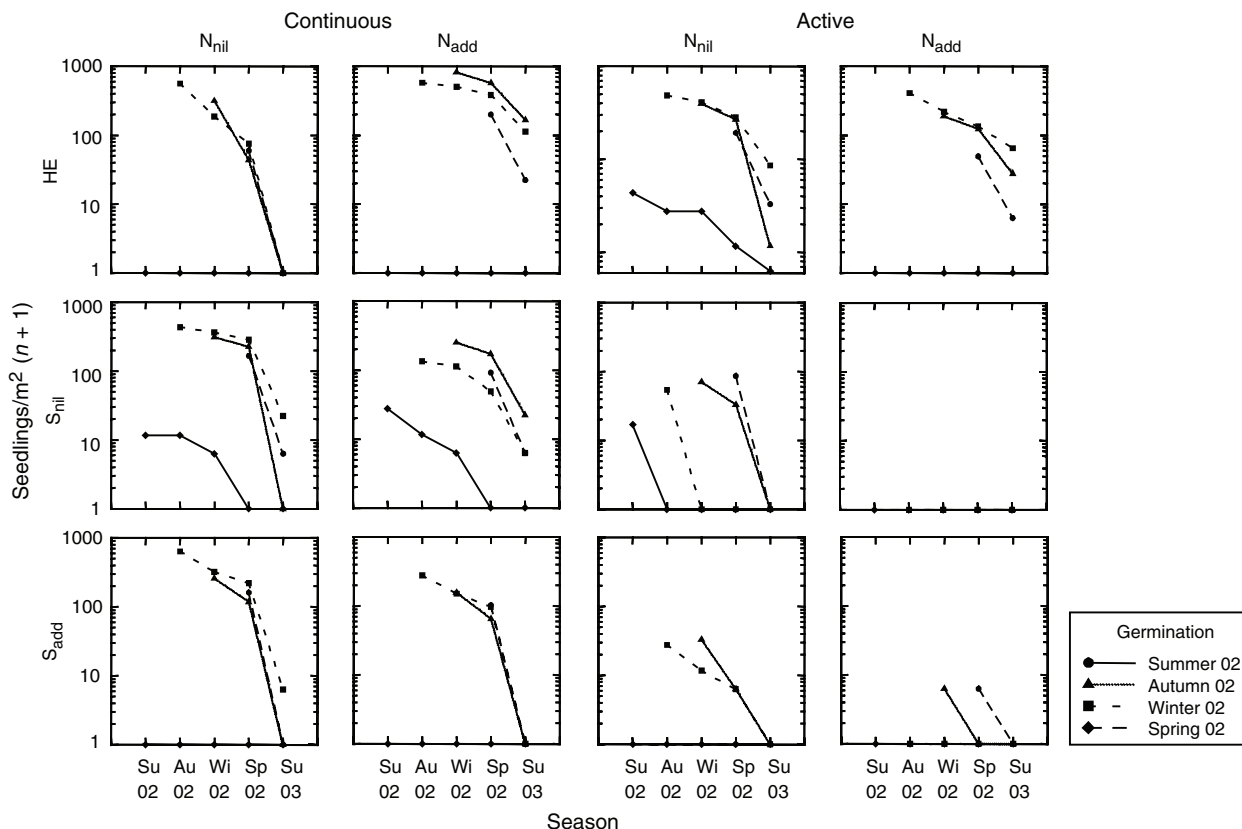


Fig. 2. Germination and survival of *N. trichotoma* seedling cohorts/ $m^2$  for grazing (continuous and active), fertility ( $N_{nil}$  and  $N_{add}$ ), and seed manipulation ( $S_{add}$ ,  $S_{nil}$ , and HE) treatments.

In spring 2002, seedlings that established in winter had a higher survival rate than those that germinated in autumn ( $P < 0.05$ ) and there was no significant effect of grazing and fertility treatments. However, survival rate was higher in the HE treatment ( $P < 0.05$ ), and this was associated with significant difference between active and continuous grazing treatments ( $P < 0.001$ ).

In summer 2003, seedling survival was very low and not affected by establishment time, grazing, or fertility treatment, but it was higher in HE treatments than in the other seed treatments ( $P < 0.05$ ). In the HE treatments, survival was higher when seedlings established in autumn rather than later in the year ( $P < 0.01$ ). However, this effect did not occur where herbicide was not applied, and a higher proportion of seedlings that established in winter 2002 survived in the  $N_{add}$  treatment than in the  $N_{nil}$  treatment, in continuously grazed treatments ( $P < 0.01$ ).

#### Seedling density in summer 2003

For seedlings that germinated in autumn, winter, and spring 2002, there were significantly more in the  $G_{con}$  treatment than in the  $G_{act}$  treatment ( $P < 0.05$ ). This difference was mainly related to higher seedling numbers in the  $G_{con}$  treatment, rather than different survival rates between treatments. The HE treatment also had more seedlings than the other seed manipulation treatments ( $P < 0.001$ ) and this was associated with higher

germination and survival rates in this treatment. More seedlings germinated in autumn 2002 than in winter and spring 2002 ( $P < 0.05$ ).

#### Seedling density and size in summer 2004

Most seedlings were 3–10 mm in basal diameter, with few >10 mm and very few <3 mm (Table 2), and there was a similar pattern of significance between the total number of seedlings and seedlings with a basal diameter of 3–10 mm. While there were more seedlings in the HE plots than in the other seed treatments ( $P < 0.001$ ), this only occurred in the actively grazed treatment ( $P < 0.01$ ). There were more large seedlings (>10 mm) in continuously grazed ( $P < 0.05$ ) and fertilised plots ( $P < 0.05$ ).

#### Factors affecting seedling numbers

Both DM and bare ground were highly correlated with *N. trichotoma* seedling numbers in autumn, winter, and spring (Fig. 3, Table 3). Density decreased linearly as DM increased, with no seedlings occurring when DM was greater than ~2 t/ha. The relationship between *N. trichotoma* seedlings and bare ground was quadratic, with maximum seedling numbers occurring at 35–40% bare ground. High seedling mortality occurred in summer when DM and bare ground were less reliable predictors of seedling numbers. TP DM and PCO axis 1 had the strongest correlation with *N. trichotoma* seedlings in

**Table 2.** *Nassella trichotoma* seedlings/m<sup>2</sup> of varying size classes (<3, 3–10, >10 mm in diameter) for each treatment, measured in February 2004  
n.s., Not significant

Grazing	Fertility	Seed	<3 mm	3–10 mm	>10 mm	Total	
G <sub>con</sub>			0	78	41	119	
G <sub>act</sub>			0	52	18	69	
l.s.d. ( <i>P</i> =0.05)	N <sub>nil</sub>		n.s.	n.s.	n.s.	n.s.	
			4	118	8	131	
l.s.d. ( <i>P</i> =0.05)	N <sub>add</sub>		0	65	29	94	
		HE	3	189	32	224	
		S <sub>nil</sub>	3	33	12	48	
		S <sub>add</sub>	1	52	12	65	
l.s.d. ( <i>P</i> =0.05)	G <sub>con</sub>	N <sub>nil</sub>	n.s.	89.7	n.s.	92.9	
			HE	0	240	21	261
			S <sub>nil</sub>	0	80	0	80
G <sub>act</sub>	N <sub>add</sub>	S <sub>add</sub>	5	117	21	144	
		HE	0	107	48	155	
		S <sub>nil</sub>	0	37	48	85	
	N <sub>nil</sub>	S <sub>add</sub>	0	91	27	117	
		HE	11	267	5	283	
		S <sub>nil</sub>	11	5	0	16	
l.s.d. ( <i>P</i> =0.05)	N <sub>add</sub>	S <sub>add</sub>	0	0	0	0	
		HE	0	144	53	197	
		S <sub>nil</sub>	0	11	0	11	
l.s.d. ( <i>P</i> =0.05)	G <sub>act</sub>	N <sub>add</sub>	S <sub>add</sub>	0	0	0	
			HE	0	0	0	0
			S <sub>nil</sub>	0	0	0	0

summer, and both these variables were closely related (Table 5), with TP DM having an inverse relationship, indicating a distinct role of perennial grasses in *N. trichotoma* seedling mortality, and PCO axis 1 had a linear relationship of similar strength.

All covariates except litter had relatively high levels of association (Table 4). Use of a multiple linear regression to determine which covariates had the most influence on seedling numbers in each season (Table 5) indicated that DM and bare ground were the main factors in autumn, winter, and spring. After substantial seedling mortality in summer, species composition (represented by PCO axis 1) was the only covariate that was significantly associated with seedling numbers.

## Discussion

In this study there was considerable variation in *N. trichotoma* seedling numbers throughout the year and among the different management treatments. Active grazing and fertiliser application promoted ground cover, pasture biomass, and perennial grass density, and were identified as factors that could limit or prevent *N. trichotoma* establishment, even when additional seed was applied. This information is crucial for the development of an integrated weed-management (IWM) system for *N. trichotoma* in native pastures. However, a key result was that no single treatment was ideal for restricting the recruitment/survival of *N. trichotoma* seedlings, which was more a function of the competitive environment that each of the treatments provided.

## Environmental factors

Time of establishment and mortality of *N. trichotoma* seedlings across all treatments was associated with predicted surface soil water content. Most establishment in autumn and winter appeared to be related to rainfall events that coincided with suitable temperature regimes for *N. trichotoma* germination in the Central Tablelands environment. In temperate grasslands, seedling establishment in autumn is common where rainfall mainly occurs in the cooler months (Grime 1979; Distel *et al.* 1992; Moretto and Distel 1998).

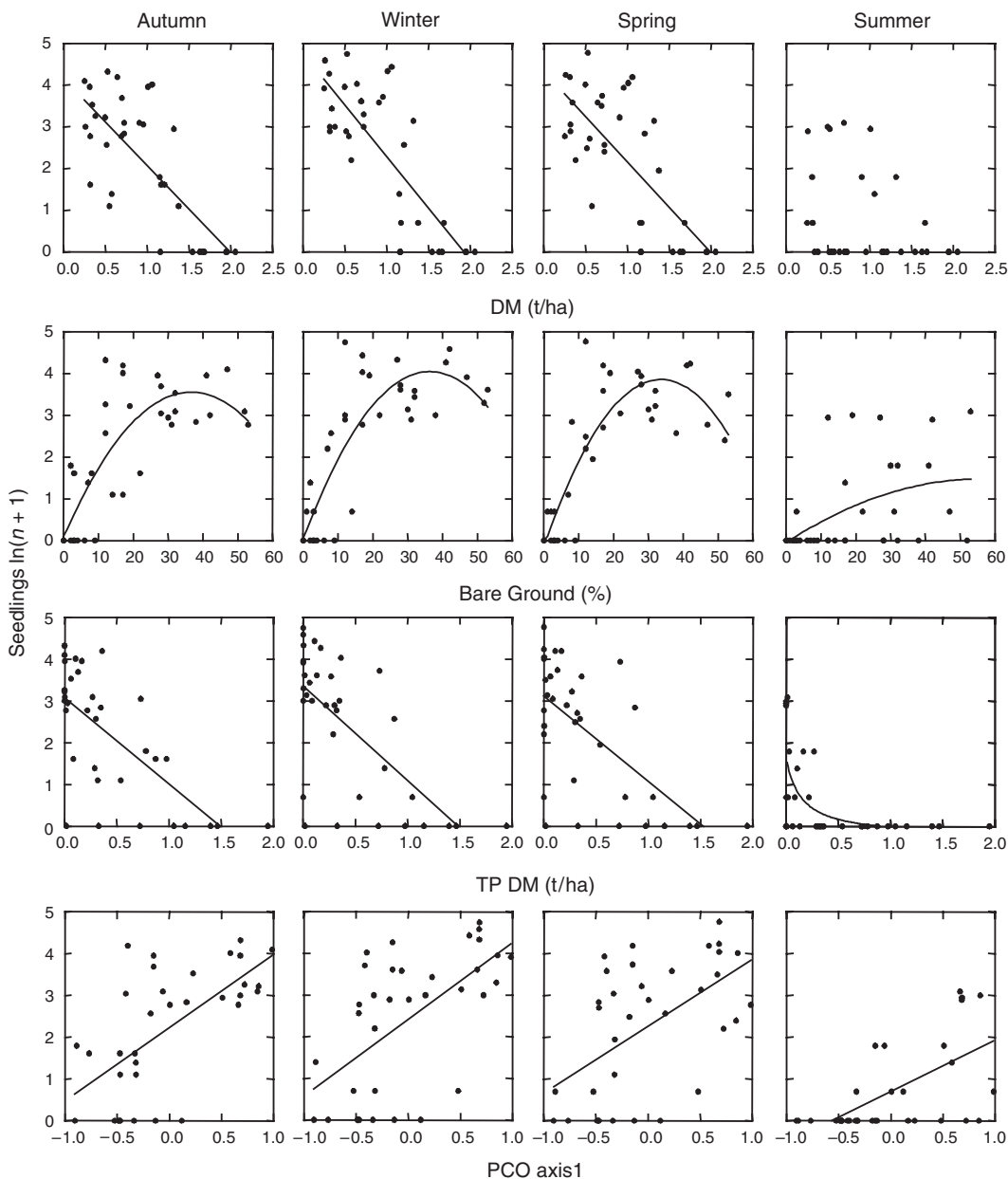
Irrespective of when seedlings germinated, mortality over summer was substantial in all treatments, probably as a result of low predicted soil water content (Fig. 1). For a period of 41 days from December 2001 to January 2002, estimated volumetric soil water was <15% (approaching permanent wilting point for the soil type) and, 24 days into this period, seedling numbers were substantially reduced. In contrast, 22 days into a 61-day period from September to December 2002, although soil water content was <15%, a substantial proportion of seedlings were stressed but alive, although temperatures were not as high as at the beginning of the same period the previous year (Fig. 1). Commonly, seedlings were able to survive 19–24 days of moisture stress in the cooler months, but for shorter periods when conditions were hotter.

Many seedlings that survived periods of surface water stress were able to establish as adult plants, suggesting that these seedlings may have developed more extensive root systems to reach moisture deeper in the soil profile. To achieve this they would probably need larger areas of bare ground that would occur in more mesic environments and so the earlier a seedling germinates the more likely it can survive through the summer period. In our study, highest numbers of seedlings germinated in autumn, and these cohorts formed the majority of the *N. trichotoma* populations. While bare ground needed to be minimal to prevent *N. trichotoma* seedlings establishing, litter levels had no effect, indicating that actively growing competitors were required to prevent recruitment.

## Effect of grazing and fertility on microsites for establishment

This experiment showed that management options could be used to reduce seedling survival, particularly that of the autumn-germinating *N. trichotoma* seedlings. For example, fewer seedlings established in autumn 2002 in treatments that were actively grazed and incorporated a rest period over summer compared with those that were continuously grazed. Continuous grazing is still widely used by producers in the Central Tablelands region of NSW (Reeve *et al.* 2000; Allan *et al.* 2003). The higher biomass maintained in the actively grazed treatments was identified as an important factor in reducing seedling recruitment, with the higher biomass comprising of C<sub>3</sub> and C<sub>4</sub> perennial grasses providing more competition to establishing *N. trichotoma* seedlings throughout the year in actively grazed treatments.

It is not possible to isolate the exact mechanism of competition from this study; however, germination suppression was likely due to reduced exposure to light levels and/or reduced temperature fluctuations, both of which can stimulate germination when soil moisture is adequate in



**Fig. 3.** *Nassella trichotoma* seedlings ( $625 \text{ cm}^2 \ln(n+1)$  transformed) compared with the 4 covariates total pasture biomass (DM), bare ground, total perennial grass biomass (TP DM), and PCO axis 1 in autumn, winter, spring, and summer 2002–03. Equations used to predict *N. trichotoma* seedlings are shown in Table 3.

autumn (Fig. 1). For *Nassella gyneriodes* (Phil.) Barkworth and *Nassella tenuissima* (Trin.) Barkworth, both of which are unpalatable species native to South America, Moretto and Distel (1998) reduced germination in microsites where plant biomass was more abundant, because of lower temperature fluctuations. Similarly, Distel *et al.* (1992) also reported that *Nassella tenuis* (Phil.) Barkworth and *Piptochaetium napostaense* (Speg.) Hack. seed collected from a grazed pasture had a higher germination than that from an ungrazed pasture, and this difference was attributed to higher temperature fluctuations.

Increasing soil fertility by applying N reduced seedling numbers in autumn. Nitrogen application also improved sward vigour, increasing competition for light, decreasing available soil water, and modifying soil surface temperature regimes rather than exerting a direct nutrient effect on seedling germination and establishment.

Adding 50 000 *N. trichotoma* seeds/m<sup>2</sup> in the previous year did not increase seedling survival, indicating that microsite conditions were more important than the *N. trichotoma* soil seedbank size in determining emergence and survival rate. This has important implications for management; rather than

**Table 3.** The equations used to predict *N. trichotoma* seedlings ( $625 \text{ cm}^2 \ln(n+1)$  transformed) from the 4 covariates total pasture biomass (DM), bare ground, total perennial grass biomass (TP DM), and PCO axis 1 in autumn, winter, spring, and summer 2002–03 shown in Fig. 2  
n.s., Not significant

Season	Covariate	Equation	P	Adj. $R^2$
Autumn 02	DM (t/ha)	$y = -2.09x + 4.16$	<0.001	0.54
	Bare ground (%)	$y = -0.0026x^2 + 0.19x + 0.077$	<0.001	0.61
	TP DM (t/ha)	$y = -1.92x + 2.91$	<0.001	0.38
	PCO Axis 1	$y = 1.76x + 2.22$	<0.001	0.39
Winter 02	DM (t/ha)	$y = -2.47x + 4.76$	<0.001	0.62
	Bare ground (%)	$y = -0.003x^2 + 0.22x + 0.051$	<0.001	0.68
	TP DM (t/ha)	$y = -2.26x + 3.36$	<0.001	0.45
	PCO Axis 1	$y = 1.85x + 2.41$	<0.001	0.34
Spring 02	DM (t/ha)	$y = -2.18x + 4.33$	<0.001	0.51
	Bare ground (%)	$y = -0.0035x^2 + 0.24x - 0.12$	<0.001	0.72
	TP DM (t/ha)	$y = -2.00x + 3.12$	<0.001	0.40
	PCO Axis 1	$y = 1.60x + 2.26$	<0.001	0.28
Summer 03	DM (t/ha)		n.s.	
	Bare ground (%)	$y = -0.0005x^2 + 0.054x - 0.044$	0.019	0.17
	TP DM (t/ha)	$y = -0.266 + 1.915/(1 + 6.86x)$	<0.001	0.34
	PCO Axis 1	$y = 1.23x + 0.70$	<0.001	0.36

**Table 4.** Pearson correlation matrix of covariates

	Bare ground	DM	Litter	PCO (axis 1)	TP DM
Bare ground (%)	1				
DM (t/ha)	-0.616	1			
Litter (kg/ha)	-0.435	0.273	1		
PCO (axis 1)	0.585	-0.487	-0.100	1	
TP DM (t/ha)	-0.547	0.736	0.320	-0.767	1

**Table 5.** Multiple regression equations predicting seedling numbers ( $625 \text{ cm}^2 \ln(n+1)$  transformed) from covariates, where S is seedling  $\ln(n+1)$ , DM is biomass (t/ha), B is bare ground (%), and P is PCO (axis 1), for all seedlings from autumn 2002 to summer 2003

Season	Equation	Adj. $R^2$
Autumn 02	$S = -1.5DM + 0.033B + 2.95$	0.61
Winter 02	$S = -1.75DM + 0.04B + 3.31$	0.70
Spring 02	$S = -1.47DM + 0.039B + 2.92$	0.59
Summer 03	$S = 1.23P + 0.70$	0.36

trying to manage seed input (often from neighbouring properties where seed production cannot be controlled) it may be more beneficial to manage soil surface conditions that can prevent or limit successful establishment.

#### Competitive mechanisms

Competition for light may have inhibited germination or caused mortality soon after germination, although this was not measured in this experiment. Joubert and Small (1982) and Talyor (1987) reported no germination difference in light and dark conditions for undamaged *N. trichotoma* seed, suggesting that competition soon after germination was more likely to have caused mortality. However, seed condition may also affect germination since

Joubert and Small (1982) found that seed with damaged lemma and palea germinated at higher rates in the presence of light than in the dark, and damage to the pericarp/testa structure increased germination in the dark. This indicated that *N. trichotoma* seed may have an in-built mechanism in the pericarp/testa to prevent germination when light is limiting. If the thickness of the pericarp/testa prevents light transmission and limits germination then buried seed may have low germination. This was consistent with the results of Healy (1945) who found that *N. trichotoma* seed did not germinate when buried at soil depths >5 mm.

In our study, pasture biomass was the most important factor affecting seedling survival in autumn and winter, but in summer 2003, species composition became increasingly important for seedling survival. The inverse relationship between standing biomass of perennial grasses and *N. trichotoma* seedlings indicated that low levels of perennial grasses (0.5 t/ha) provided sufficient competition for seedling mortality to occur during dry summers. Competition for light may be more important earlier in the season, but as soil water and nutrient resources are depleted, competition for these resources may become increasingly important. Perennial grasses are likely to deplete these resources not only at the soil surface, but also at depth. Aguilera and Lauenroth (1995) found that microsites that did not have shoot or root competition had higher soil water content in the top 50 mm of the soil in a semi-arid grassland dominated by *Bouteloua gracilis* (H.B.K.) Lag. ex Steud. In our study, estimated available soil moisture was very low over summer.

Soil N was measured annually (Badgery et al. 2008), but not seasonally, and so it was not possible to determine seasonal fluctuations in N. Chen et al. (1999) reported that, for pastures in the Northern Tablelands of NSW, total soil N in the top 50 mm of the soil profile varied substantially throughout the year, but little among different introduced pasture types. Highest levels were measured in summer, decreasing to a minimum in mid to late spring at the end of



the main pasture growth phase. In our experiment, N deficiency was likely to coincide with the beginning of the major period of soil water deficiency and hence it was difficult to determine whether competition for soil N also plays a role in seedling mortality. However, since there was no significant difference in survival to summer 2003 between the high and low fertility treatments, soil moisture was the more likely mechanism of competition, although grazing and other unmeasured microsite factors may have masked any relationship with soil N.

### Herbicide

Herbicide application was the only treatment that significantly affected the number of seedlings that survived until summer 2003. Grazing was an important factor in autumn and winter, but most seedlings died by summer. Application of flupropanate resulted in significant mortality of native perennial grasses, in particular the C<sub>3</sub> species (Keys and Simpson 1993; Campbell and Van de Van 1996; Badgery *et al.* 2008). These species contributed substantially to ground cover and, when removed, competition was considerably reduced. Breakdown of plant residues in the herbicide treatment may have increased soil fertility, which when combined with the decreased competition, resulted in seedlings that were more developed by summer.

Flupropanate is a residual herbicide that can remain active in the soil for 5 (Anon. 1973) to 23 (Viljoen 1999) months when applied at 1.49 kg a.i./ha. Dissipation of the residual effect is related to amount of rain diluting/leaching it from the soil and so, seedlings that germinated 6 months after herbicide application, survived in this experiment. Further, residual control of *N. trichotoma* seedlings by flupropanate may not compensate for the altered grassland structure that promotes seedling germination. This may not be an issue in dense *N. trichotoma* stands where there are very few other species, but where there is a reasonable proportion of native grass, then spraying with flupropanate could promote *N. trichotoma* invasion in the future.

### Managing *N. trichotoma* seedlings

Some broad implications from this study should be considered in the development of an IWM strategy for *N. trichotoma* control. The use of 1.49 kg a.i./ha of flupropanate to control adult *N. trichotoma* plants is commonly recommended for non-arable grasslands (Campbell and Gilmour 1979; Campbell and Vere 1995). However, despite the residual effects of this herbicide, our results indicated that this practice was likely to substantially increase the germination and establishment of *N. trichotoma* seedlings in the mid to long term. This may partly explain why relatively rapid re-invasion has been commonly observed after herbicide application. For effective on-farm practice, control of adult *N. trichotoma* plants should be undertaken with methods that minimise collateral damage to desirable pasture species, while limiting the re-establishment potential of seedlings. Grazing-management tactics that maintain pasture biomass can increase competition from more desirable perennial grasses, substantially slow the re-invasion of *N. trichotoma* in native grasslands, and prevent invasion into new

areas by reducing survival of germinating seedlings. Such grazing-management techniques should maintain high ground cover (approaching 100%) and a pasture biomass >2 t/ha. However, in practice, this is often difficult to achieve and so concentrating on management that promotes desirable perennial grasses that can out-compete seedlings in the critical summer months may be a better focus. This could be achieved using grazing tactics that incorporate short, intense grazing periods combined with long, strategically timed rests. A reduction in stocking rate below normal levels, in the first year or 2 of an IWM strategy, could benefit desirable perennials at the expense of *N. trichotoma*. The key point is that in summer the desirable, competitive native grass biomass needs to be >0.5 t/ha to cause mortality to *N. trichotoma* seedlings. Creation of that level of competition probably needs to start in spring, when soil moisture levels are adequate for plant growth. However, in practice, maintaining biomass levels at >2 t/ha to prevent establishment, and perennial grass biomass at >0.5 t/ha to prevent survival, is unlikely to be completely effective because it would not always be possible to achieve these biomass levels over a whole paddock, particularly in variable landscapes.

Our results for *N. trichotoma* in a temperate environment were similar to those of Moretto and Distel (1998) in a semi-arid environment, who found that the mortality of *N. gynerioides* and *N. tenuissima* seedlings was primarily related to desiccation, resulting from competition from companion species.

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