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Low Cost Rehabilitation of Perennial Grass Pastures by Managing Seedling Recruitment

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Abstract

Many permanent pastures across southern Australia have suboptimal levels of perennial grass species, below that required for sustainability; yet replacing those species by conventional means is often unprofitable. This project in Central New South Wales aimed to identify low-cost, ecologically-based management options that enabled the successful recruitment of perennial grass seedlings within existing pastures for the native grasses (*Austrodanthonia* spp. and *Bothriochloa macra*) and an introduced grass (*Phalaris aquatica*). Successful recruitment for all species in early autumn, during the drought years of this project occurred, provided quantities of germinable seed were available (rest paddocks from spring to promote flowering and seed set), a suitable rainfall event resulted in a 7-15 day period of moisture in the surface soil occurring after seed matures and falls (~50-80 mm rain over 7 rain days, spread through 10-11 days, higher at hotter sites) and an appropriate microsite (a light scarifying on non self-mulching soils) was present for emergence of seedlings. Insecticide may be needed to control seed-harvesting ants in phalaris and herbicides occasionally in some cases. Climate analyses using a soil moisture model, indicated that most years would result in some recruitment. These techniques can be used to significantly increase the perennial grass content of pastures across south-eastern Australia at low-cost to sustainability levels, with substantial impacts on medium to long-term profits and environmental benefits.

Executive Summary

Australia has over 400 million ha of grazing lands that cover 70% of the continent upon which the majority of livestock depend for forage. These grazing lands, particularly in south-eastern Australia, are based on native and introduced perennial grasses. Perennial grasses are the integral components of grazed pastures as they provide more stability than pastures based on annual species due to better ground cover, green forage for longer periods, reduced land degradation (soil acidity, salinity, erosion) and minimised weed growth if their proportion is 60% or more. Many pastures are though below sustainability levels, surveys typically only find 20% perennial grass where these species are present, associated with lower than possible livestock carrying capacities. Improving the perennial grass content in pastures has previously been done by resowing, but in many areas that is marginally or not profitable, for beef or sheep production. The alternative is to develop low-cost, ecologically-based management practices for existing pastures where desirable perennial grass species are present that enable the recruitment of seedlings from seed set by the existing plants, such that over time the perennial grass content can reach desired levels.

This project investigated a three-phase approach to managing recruitment designed to; encourage seed set and delivery by desirable species, to prepare more suitable micro-sites for seedling recruitment and to identify the better post-emergence tactics that aided seedling recruitment in the short to medium-term. The project was done as a PhD study (Thapa, 2009) with Charles Sturt University, Orange to which the reader is referred for the full details of what is summarised in this report. Research was done on the introduced grass phalaris (*Phalaris aquatica*, C3 at Orange) and the native grasses, red grass (*Bothriochloa macra*, C4 at Wellington) and wallaby grass (*Austrodanthonia* spp., C3 at Trunkey Creek). Five field experiments were done at three field sites, supplemented by additional lab and field studies, over three drier than average years in Central New South Wales in existing pastures of these species. In all field experiments successful recruitment of the desirable species resulted, though the drought meant that few seedlings survived for more than a year. The project focused on the conditions that enhanced the recruitment of seedlings. An irrigation experiment, repeated throughout the year at all three field sites where shaded plots were irrigated over two days to simulate rainfall conditions, helped to establish the minimal conditions required for recruitment. Soil moisture modelling was done to identify the minimum climatic conditions required to achieve a successful recruitment event and the probabilities of successful events estimated from long-term rainfall data.

Key messages:

- The results were similar for all three species studied and common principles were established to enable successful seedling recruitment.
- Maximising current seed set is critical for successful recruitment as there was limited germinable seed in the soil seed bank. Rest paddocks from spring to maximise flowering, seed set and maturity.
- Seed production is low during dry years and hence the numbers of seedlings establishing through those years will be less than could be achieved if extra seed was supplied, but still useful for increasing the perennial grass content if there is sufficient rainfall over the following year.

- Seedling recruitment was greater where there was:
    - more seed set (rest paddocks from spring),
    - more (uncut / ungrazed) herbage mass was present in intact swards,
    - where some soil disturbance (light scarifying) on non self-mulching soils occurred (this did not apply for the phalaris experiment, as in that case the soil was naturally self-mulching) – scarifying to be done at seed maturity,
    - insecticide to control seed-harvesting ants (if a problem as is often the case with phalaris), and
    - herbicide at low rates at seed maturity, but before recruitment, to weaken plant competition and, or control existing weed problems, may apply in some cases.
- The surface soil (top 5cm) needs to be moist for >7 days and ideally 15 days to enable a high density of perennial grass seedlings to establish. In all five experiments suitable conditions occurred around late February and through March each year, despite the dry seasons. These soil conditions resulted from 50-80mm (more rain needed at the warmer site at Wellington) of rain over several days. Periods of 2 dry surface soil days in a 15 day period did not seem to limit recruitment.
- Analysis of the last 30 years of rainfall at each site found that the minimal requirement of 7 days of adequate surface soil moisture occurred in late summer, early autumn in 98%, 92% and 72% of years at Orange, Trunkey Creek and Wellington, while 15 adequate soil surface moist days occurred in 78%, 44% and 30% of years, respectively. This indicates that useful recruitment would occur in most years.

Conditions for seedling survival through the following year were not resolved due to the drought. Future work needs to investigate the interaction between plant competition and soil moisture conditions on seedling survival within existing swards.

This work showed that in most years it would be useful for farmers to rest targeted paddocks from spring to enable opportunities for recruitment. Seasonal conditions need to be monitored. If possible farmers should persevere until late March to determine if successful recruitment had occurred before continuing or abandoning, resting a paddock. Typically the forage for grazing only becomes restrictive to livestock by late summer and autumn. Thus in dry years seedling recruitment and survival is less likely but a rested paddock has then some forage available that can be used in autumn. In wet seasons there is usually no shortage of fodder and resting the paddock for longer periods is not a major difficulty. The paddock would be out of use for less time than applies if sown to a pasture. After locking up paddocks they need to be monitored to decide if intervention is needed for scarifying, insecticide or herbicide treatments. Typical costs would be about 10% that of sowing a new pasture. A decision chart has been developed to guide farmers and their advisors in using the information gained in this project.

A consideration of climates throughout south-eastern Australia suggests that the principles developed in this project will apply in many areas. Rainfall events from late summer, through autumn occur in many of those districts. The grasses studied in this project are known to exist throughout the south-east and do naturally recruit. This work suggests that much of that recruitment is probably occurring in late summer and autumn. In different districts some preliminary work would though be needed to determine if the techniques coming from this project need any modification.

Farmers are now in a position to more reliably enable recruitment of desirable perennial grasses within their pastures. The outcomes can be achieving 60% perennial grass at significantly lower-cost, at which improved production and environmental outcomes can be achieved.

Contents

1 Background

The loss of perennial grasses from the grasslands of southern Australia and replacement by annual species (attributed to management practices - Moore, 1970) has had severe implications for the productivity of livestock enterprises through weed invasion, erosion, salinity, acidity and nature conservation (Kemp *et al*., 2000; Michalk *et al*., 2003). Sustainability of these grasslands is of major concern to landholders, researchers and the community at large. Previous research [Temperate Pasture Sustainability key program (TPS) and Sustainable Grazing Systems program (SGS)] has demonstrated that sustainable pastures are those that are based on perennial grasses (Kemp and Dowling, 2000; Mason and Kay, 2000). However, the current perennial content of many pasture systems is commonly low, often accounting for ≤ 20% of pasture composition which is well below the level (60+%) that is desired for sustainability (Kemp and Dowling, 2000).

This situation in permanent pastures across southern Australia is evident in other parts of the world that have sub-optimal levels of perennial grass species, below thresholds required to sustain ecosystem function. The long-term sustainability of these perennial pastures is dependent on the successful recruitment of plants of the same species or a similar species with a comparable function. Recruitment can be promoted with either better knowledge of how the ecosystem functions and of the manipulation techniques required to optimise the process, or by a replacement approach of re-sowing productive perennial grass species. The principal difference between these practices is that the former may take longer. However, using an ecological approach is less costly than resowing, particularly on less fertile and low rainfall soils. With declining terms-of-trade for livestock production and increasing climate variability leading to increased risk, the relative cost of re-sowing has become more marginal except on more fertile soils and in higher rainfall environments where the chances of success are greater.

Recent national research programs (TPS and SGS) have concentrated on increasing the perennial grass content using tactical management (Kemp *et al*., 2000, 2003). Much of that work has developed effective management practices that maintain existing plants in a productive state, but has not provided insights into how existing plants are replaced through seedling recruitment (Kemp *et al*., 2000). The later requires a better understanding of the population dynamics of perennial species which received little attention in earlier work. Pastures based on perennial grasses can be sustained in the short-term through reducing the grazing pressure and encouraging vegetative growth, but may fail to recruit new seedlings in the absence of suitable environmental and management conditions. The result is the degeneration of pastures over time and the need for the establishment of new pastures through re-sowing, at a considerable cost to farmers.

Understanding how to encourage recruitment of new seedlings into existing swards is a substantial knowledge gap in grassland ecology. Limited research has shown that there is often low or nil survival of desirable grass seedlings in existing paddocks which reflects a poor understanding of the mechanisms underlying the recruitment process. In a study of seed dormancy, germination, seedling emergence and survival of perennial pasture grasses in northern New South Wales, Lodge (2004) posed the challenge of identifying the causes that lead to limitations in successful recruitment. This clearly highlighted the need for more research to devise appropriate and practical management options to encourage the emergence and survival of new seedlings into pastures.

The work of Lenz and Facelli (2005) in South Australia on recruitment of both native perennial grass and exotics further identified the need for research to look into the reasons behind the low survival of perennial grass seedlings.

Pasture inputs costs can be substantially reduced by managing perennial pastures to successfully recruit new plants, which can extend their life or even remove the need for re-sowing. The cost of re-sowing, a key strategy for rehabilitating perennial pastures, is proving to be prohibitive and there always is short term loss of production. The average cost is now \$300 ha^{-1} and it generally takes 8-10 years to recover costs (Vere *et al*., 1997; Bolger and Garden, 1998) in many areas where site productivity is only moderate. A majority of farmers surveyed in the high rainfall temperate zones of Australia though, still believed that it was worthwhile re-sowing old or degraded pastures though they do not always make a profit on them (Reeve *et al*., 2000). This indicates that a decline in productivity has occurred and farmers are keen on restoring paddocks to a desired level. To date their only option has been to contemplate resowing. Many degraded pastures still have a residual of desirable perennial grasses that could be used as the base for seed production and recruitment of new plants once it is known how best to manage that process.

Simple low-cost management procedures that enhance the perennial grass content are required. These procedures should target: (1) the successful production of viable seeds, (2) the successful delivery of those seeds to the soil surface where establishment can occur and (3) then the successful recruitment and survival of young plants. That suggested a three-phased approach to managing recruitment will be necessary to enable successful recruitment.

2 Project Objectives

i. Develop basic information on low-cost management practices to successfully re-establish perennial grass plants within typical native/naturalised grasslands of central New South Wales without resowing.

ii. Develop a print ready producer publication on the recommended practices.

iii. Run two open days at research field sites providing a research update demonstrating the processes required for low cost rehabilitation of perennial pastures.

3 Methodology

This project involved a series of inter-related field experiments at three sites in central NSW, plus additional small scale studies to investigate specific issues and then climatic analyses to assess the conditions that resulted in successful recruitment within the experiments done and then the probability of those events in practice.

The project focus was on the central tablelands and nearby slopes in central NSW with three field studies on native and introduced perennial grasses that are widespread and important for grazing in the region. The phalaris (*Phalaris aquatica*, C3*)* site was on the CSU Campus in Orange, the red grass (*Bothriochloa macra*, C4) site at Wellington and the wallaby grass (*Austrodanthonia* spp. C3) site at Trunkey Creek. C3 and C4 species were included to investigate the likely range in responses. Across the field sites the aim was to have a range of competing plant species that included other perennial grasses (the same species, or others), annual grasses (the most common competitors) and broadleaf species.

The treatments in the main field experiments were designed to investigate each of the key phases of seedling recruitment in sequence, with factorial combinations of seed delivery, viable seed levels and site preparation as treatment factors. The experiments were laid out in a randomised block design with 4 replicates. The phalaris and wallaby grass experiments were repeated over two years. Only one year was possible at the red grass site due to the unavailability of the site from the second half of 2008.

Treatment Factor A: Seed delivery mechanisms - Pre-emergence phase

i. **UC: Uncut (control)** - The sward was left uncut or ungrazed (UG) in the case of red grass experiment.

ii. **CL: Cut & leave** - Standing plant material was cut to 20-50 mm above ground but plant material and seed heads were left on the ground. This aimed to increase the litter level, which could retain more moisture near the soil surface and also maximise the number of seeds on the ground at one time. A large amount of seed reaching the ground at once could limit the ability of seed harvesting ants to completely remove them and enable some seeds to germinate. *[The red grass site had CL replaced by a pasture cropping (PC) treatment. At the wallaby grass site, CL was completely removed as the differences between a CR Vs CL were minimal and CR provided the more useful comparison with the control.]*

iii. **CR: Cut & remove** - Herbage mass was reduced to a level similar to grazing by cutting to 20-50 mm above ground and plant matter removed. This aimed to simulate the physical movement from grazing that would have caused some seeds to drop to the ground, while others could be consumed. *[At the red grass site CR was modified into grazed (GR) treatment.]*

Treatment Factor B: Modifying viable seed levels

i. **NS: No seed addition (control)**

ii. **IS: Insecticide application** - Dead seeds treated with insecticide were added to limit predation from ants on existing viable seeds. These seeds were tested for germination (no germination recorded) before applying in the field. Phalaris seeds were used as they are very attractive to ants (Campbell, 1966; Campbell and Gilmour, 1979). *[IS was dropped at the red grass site because ants were not a major problem (W B Badgery, pers. comm.).]*

iii. **SA: Seed addition** - Extra seeds (~50 kg ha^{-1}) were added to test if recruitment was seed limited. The aim was to flood the system with additional seeds.

Treatment Factor C: Site preparation and reducing competition

i. **NP: No preparation (control)** - The plot was left unmodified.

ii. **HA: Herbicide application** - A sub-lethal dose of grass herbicide was applied to weaken competition from adult plants and to kill any annual grasses that were germinating.

iii. **SR: Scarify & rake** - The ground surface was lightly scarified to remove small competitors and existing adult plants. Approximately 50% of the plot area was scarified uniformly to create more bare ground and rougher soil surfaces which could become potential microsites for seedling recruitment. This treatment aimed to simulate the soil disturbance created by cattle and sheep hooves during grazing periods and, or by light tillage to create microsites that may be favourable for germination under suitable climatic conditions. This treatment also changed the location and density of litter biomass. *[At the red grass site, SR was removed as it was incorporated within the pasture cropping treatment within treatment factor A.]*

3.1 Data collection and analyses

All the field sites were characterised in terms of botanical composition, soils and climate. Climate data were collected with data loggers at each site for the duration of each experiment.

Field experiments were focused on fine scale effects on plant recruitment. Plots were 2 x 2 m within which 0.9 x 0.9 m area in the centre was permanently marked for routine measurements. The 0.9 x 0.9 m area was subdivided into nine 0.3 x 0.3 m contiguous quadrats (arranged in a 3 x 3 square) and used for BOTANAL measurements. Each quadrat was further divided into 3 x 3 sub-quadrats, each 0.1 x 0.1 m, to give 81 sub-quadrats arranged in a 9 x 9 square within the 0.9 x 0.9 m permanently marked area. Seedling numbers were recorded in these sub-quadrats. Treatments were applied over the whole 2 x 2 m plot.

Dry weight ranks of the 3 most abundant species and the total dry matter (DM) of all species were estimated using BOTANAL procedures (Tothill *et al*. 1992). Dry weights of standing DM (t ha^{-1}) and litter DM (t ha^{-1}) were estimated separately. Sampling for pasture biomass was done every 3 months in late summer (February), autumn (May), winter (August) and spring (November) each year. Plant cover, litter cover, and bare ground percentages were visually estimated. Within 2-3 weeks of seeds germinating (after treatment application), initial seedling counts were done; then 6, 24, and 52 weeks later. Within the plot, 2 soil cores (0.05 m diameter x 0.05 m deep) were randomly collected - one from each side of the 0.9 x 0.9 m area used for measurements and grown in the glass house for seed bank studies at the start of each experiment. The total number of plants and seedheads in each of those plants were counted in 10 randomly selected 0.3 x 0.3 m quadrats at the time of seed maturity. From these plants 10 seedheads were collected and seeds counted to estimate the amount of seed per seedhead and total seed production.

Data analyses were done using a range of statistical techniques with Systat and Genstat. Spatial techniques were used to analyse seedling density data as there were significant gradients in recruitment rates across sites that were not treatment related.

3.2 Soil moisture model

Soil moisture potential at each site was measured using gypsum block located at a depth of 50 mm, but the data obtained had errors, was missing for some periods and was deemed insufficient to characterise soil moisture trends. The moisture content (as percent volume) in the top 50 mm soil surface during the experiment and for the past 30 years at all the three sites was estimated using the Sustainable Grazing Systems (SGS) pasture model (Johnson *et al*., 2003; using V 4.5.4, Johnson, 2008). The SGS model uses daily climate data (rainfall, temperature, relative humidity, wind speed, vapour pressure, evaporation, solar radiation), soil physical properties based on the generic soil type, soil nutrient based on the initial inorganic status (NO_3 and NH_4), pasture species and latitude to calculate soil moisture values for the period defined in the model. When data was not available for parameters the model uses the generic patterns based on the latitude, longitude and other relevant factors. The analyses focused on the soil moisture conditions in the top 50 mm created by the rainfall events that started immediately before the time of the identified recruitment events. The long-term climate data for Orange were obtained from the National Climate Centre of the Australian Government Bureau of Meteorology (NCC, 2009). For Trunkey Creek and Wellington, the long-term data were estimated from the Datadrill® program that predicts climate data from given co-ordinates from surrounding weather stations (Jeffery *et al*., 2001).

4 Results

4.1 Phalaris experiments (Orange)

4.1.1 First year (2006-07)

There was a large recruitment of phalaris seedlings in early March 2006 (Figure 1) after rainfall events in the preceding months (Jan: 39 mm; Feb: 57 mm). As many as 1300 seedlings m^{-2} were recorded where the uncut, insecticide and no preparation treatment applied. On average, 222 seedlings m^{-2} established at the site. This followed a high seed set.

Uncut (UC) treatments had more phalaris seedlings germinated than cut & leave (CL) treatments, which had marginally higher seedling numbers than cut & remove (CR) treatments ($P<0.001$). Fewer seedlings germinated in treatments where no seed was added (NS) than insecticide applied (IS) or seed added (SA) ($P<0.001$). IS and SA did not significantly differ but more seedlings were observed in IS than SA when herbicide was applied ($P<0.05$). Herbicide application (HA) treatments yielded marginally more seedlings than no preparation (NP) or scarify & rake (SR) treatments ($P<0.05$). No significant difference occurred between NP and SR except under CL when less seedlings were observed in SR than NP ($P<0.05$). Within UC, both IS and SA increased seedlings in SR; within CR, IS had more seedlings germinate in HA whereas there were more in NP for SA; and within CL, IS enhanced seedlings in NP but SA had more in HA or SR ($P<0.001$). Young plant survival across treatments followed similar trends to seedling numbers. At 6 weeks after emergence UC still had higher seedlings than either CL or CR ($P<0.001$). IS or SA had more seedlings surviving than NS ($P<0.001$) but equal numbers of seedlings were surviving in NP, HA or SR. All the significant interactions observed during emergence across treatments were present at this stage for surviving seedlings. At 24 weeks after emergence, low numbers of seedlings were surviving across treatments. As earlier, UC had more seedlings surviving than CL or CR (P<0.001) but NS, IS or SA were not significantly different. HA or SR had marginally less seedlings surviving than NP (P<0.05) except under CR when there were more seedlings surviving in HA than SR.

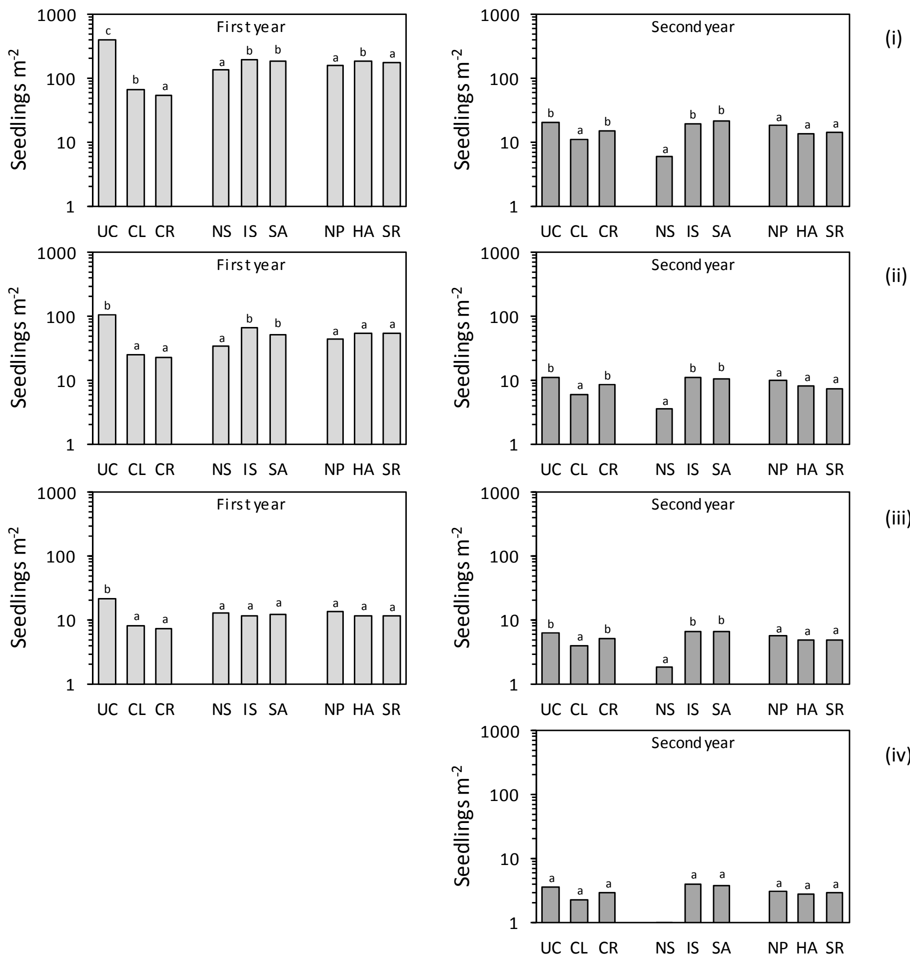

Figure 1. The average number of phalaris seedlings m^{-2} (logarithmic scale, n + 1) in (i) March, (ii) 6 weeks after emergence, (iii) 24 weeks after emergence and (iv) 52 weeks after emergence across UC (uncut), CL (cut & leave), CR (cut & remove), NS (no seed), IS (insecticide application), SA (seed addition), NP (no preparation), HA (herbicide application) and SR (scarify & rake) treatments for both first (2006-2007) and second (2007-2008) year experiments; (where the same letter appears on a column within each subset of treatments in the same year, results are not significantly different, P<0.05); no seedlings were surviving for first year experiment at 52 weeks after emergence.

In general, the examination of individual relationships from multiple regression indicates that greater herbage mass (>2-3 t ha^{-1}) but less green DM (<1.5 t ha^{-1}) and more plant cover (30-70%) or litter DM (~2-3 t ha^{-1} or 40% as litter cover) were associated with maximum numbers of phalaris seedlings at emergence for the first year experiment. Use of regression trees across all treatments showed that when all factors (standing DM, functional groups DM, green DM, litter DM, bare ground, plant cover) were included, the total standing DM and plant cover were the more important factors determining overall seedling numbers (Figure 1). Where DM was less than 3.9 t ha^{-1} seedling numbers were approximately 20% (~100 m^{-2}; n = 709) of those where the DM was >3.9 t ha^{-1}. Plant cover was the next most important criteria in determining seedling numbers. Seedling numbers were doubled (~800 m^{-2}; n = 77) when plant cover was above 45% compared with below 45%. Green DM and litter did not emerge as major factors in the regression tree analyses, suggesting that they may have been significant in the analyses of individual factors through their association with total DM and plant cover, but dropped out of this multivariate analysis. The proportional reduction in error was reasonable (0.39) suggesting that there were still a range of additional factors that determined seedling emergence, but they were probably not consistent across all treatments. At 24 weeks after emergence in general, existing standing DM (~3 t ha^{-1}) with lesser green DM (<1 t ha^{-1}), plant cover (30-55%) or litter DM (~2-3 t ha^{-1}) had maximum number of phalaris young plants surviving (Figure 3); these values were more or less similar to where better results in initial seedling numbers were obtained. However across all treatments regression tree analysis predicted green DM was the more important factor in determining overall number of young plants surviving 24 weeks after initial emergence. Where green DM was <0.7 t ha^{-1}, average young plants surviving were 9 m^{-2} (n = 606) and above 0.7 t ha^{-1} green DM had on average 31 m^{-2} (n = 366) young plants surviving. But due to the drought that then followed effectively no young plants survived to 52 weeks after emergence in the first year.

The general conclusion from this experiment was that minimal intervention was needed to maximum recruitment and survival of seedlings from early autumn till early spring. There were small effects from using insecticide to control seed-harvesting ants and small advantages from a sub-lethal dose of grass herbicide

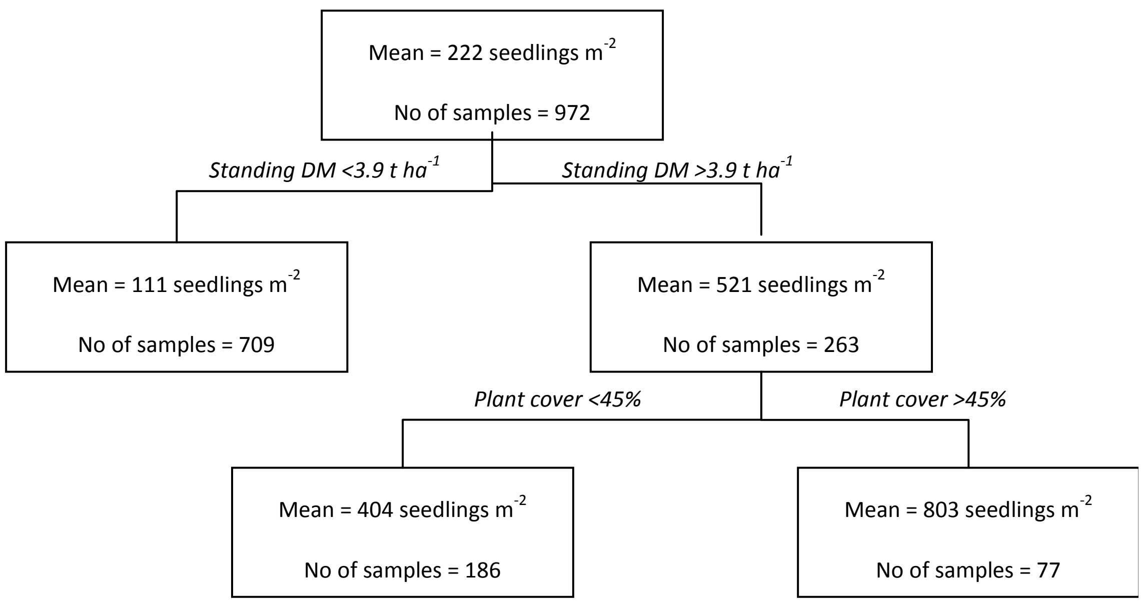

Figure 2. Initial phalaris seedling emergence (m^{-2}) in March 2006 (first year) as predicted by standing biomass (DM t ha^{-1}) and plant cover (%) across all treatments (standing DM, functional groups DM, green DM, litter DM, bare

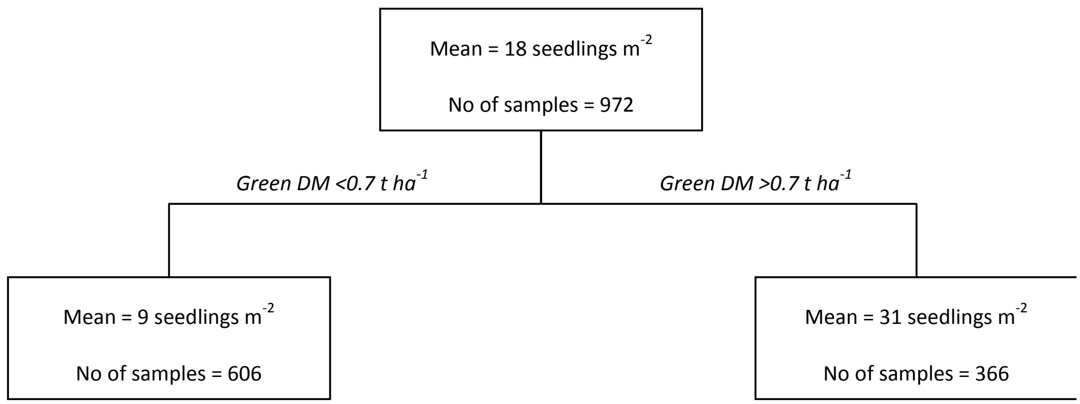

Figure 3. Surviving phalaris young plants (m^{-2}) 24 weeks after emergence in August 2006 (first year) as predicted by green biomass (DM t ha^{-1}) across all treatments (standing DM, functional groups DM, green DM, litter DM, bare ground, plant cover were included in the model). Proportional reduction in error (PRE) = 0.13.

Second year (2007-08)

Similar to the first year results, the second year experiment recorded recruitment of phalaris seedlings during early March 2007 (Figure 4) after significant rainfall during the preceding months (Jan: 54 mm, Feb: 90 mm). The second year experiment did not result in as much seed set or as many seedlings as the first year but there were seedlings across all treatments and not only in the plots with uncut swards, the more successful treatment in most of the first year plots. The highest seedling number recorded was 198 seedlings m^{-2} in the plot with uncut, insecticide and herbicide treatments applied. The second year experiment had a better success in terms of young plant survival than the first year experiment. Though there was far less recruitment, 27 seedlings m^{-2} on average across the site, the decline through the year was only gradual. At 24 weeks after emergence there were on average 6 young plants m^{-2} remaining across the site. Some young plants died but there were still 3 young plants m^{-2} across the site at 52 weeks after emergence. The plot where the sward was uncut, insecticide and herbicide applied had the highest number of young plants (20 m^{-2}) surviving, which also had the highest initial recruitment.

Fewer seedlings germinated in CL than in UC or CR ($P<0.001$). UC and CR did not significantly differ though UC had more seedlings. Similar to first year, IS or SA generated more seedlings than NS ($P<0.001$). No difference in seedling numbers existed between IS and SA (same as the first year) except within UC (more seedlings in IS than SA) and CL (more seedlings in SA than IS) ($P<0.001$). In contrast to the previous year NP, HA or SR did not differ in seedling numbers except under UC when fewer seedlings germinated in HA or SR than NP ($P<0.05$). All differences across treatments during emergence continued through young plant survival at 6 weeks and 24 weeks after emergence. At 52 weeks after emergence, there were very few young plants surviving. Similar numbers of young plants were surviving in UC, CL or CR. Within UC, fewer seedlings were present in HA or SR than NP whereas more young plants were surviving in HA within CL ($P<0.05$).

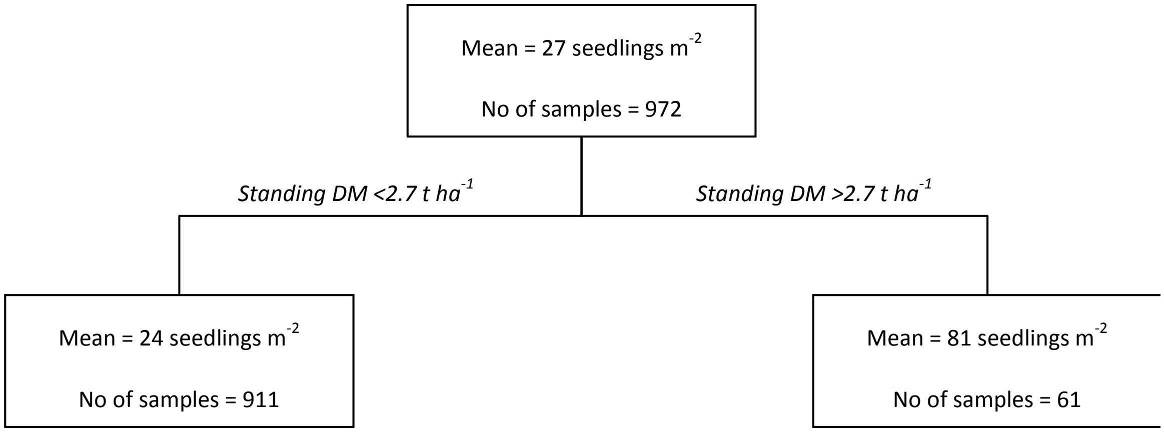

Figure 4. Initial phalaris seedling emergence (m^{-2}) in March 2007 (second year) as predicted by standing biomass (DM t ha^{-1}) across all treatments (standing DM, functional groups DM, green DM, litter DM, bare ground, plant cover were included in the model). Proportional reduction in error (PRE) = 0.06.

IS or SA had more young plants surviving than NS (P<0.001), the trend which continued since first emergence.

In general, there were less seedling numbers in the second year than were observed in the first year. However, seedling numbers at emergence were associated with similar factors. Plant cover (>15%), herbage mass (1-3 t ha^{-1}), and less green DM (~0.5 t ha^{-1}) or litter DM (~1.5 t ha^{-1}) maximised phalaris seedling numbers as shown in the individual significant relationships. Use of regression trees across all treatments and factors found the only important factor in predicting seedling numbers at emergence that applied across the whole experiment was total standing DM (Figure 4). The cut off value was 2.7 t ha^{-1} below which 24 seedlings m^{-2} (n = 911) and above which 81 seedlings m^{-2} (n = 61) were present on average. The lower values than for the first experiment would reflect the drier year. At 24 weeks after emergence in general, lower numbers of young plants were surviving in the second year than were observed in the previous year but surviving young plants were associated with similar factors. Plant cover (~55%), litter DM (~2 t ha^{-1}) or standing DM (~2 t ha^{-1}) maximised survival of young plants 24 weeks after emergence. Regression tree analysis however failed to identify any one most important factor; this may be because of the low survival rate for these young plants. At 52 weeks after emergence, low numbers of surviving plants made it difficult to discern which treatments enabled better survival of young plants. Treatments had similar number of young plants surviving which indicates factors other than microsites (defined by plant cover, litter, bare) and competition (green, functional groups) may be affecting survival.

As with the first phalaris experiment the general result was for those plots with minimal intervention to record higher seedling numbers through from emergence in early autumn to early spring. Both insecticide and herbicide applications made small improvements.

4.2 Wallaby grass experiments (Trunkey Creek)

4.2.1 First year (2007-08)

Wallaby grass seedlings germinated and established in early March 2007 (Figure 5) after summer rainfall in the preceding month (Feb: 93 mm). Due to the dry season there was very limited seed set. The greatest seedling number (296 m^{-2}) was observed where the sward was uncut, extra seed added and the soil surface layer disturbed through scarify & rake. Survival of emerged wallaby grass seedlings was very low. On average, only 24 seedlings m^{-2} germinated at the site but there were only 2 seedlings m^{-2} (on average) remaining at the end of 6 weeks after emergence. However, these seedlings survived through the year and there was 1 seedling m^{-2} (on average) surviving at 52 weeks after emergence. The treatments where the sward was uncut, extra seed added and herbicide applied had the highest number of seedlings (19 m^{-2}) surviving.

Wallaby grass had marginally more seedlings germinated in cut & remove (CR) treatments than uncut (UC) treatments ($P<0.01$), possibly due to a non-significant interaction with seed addition treatments. Seed addition (SA) treatments significantly increased seedling numbers compared to no seed addition (NS) or insecticide application (IS) treatments ($P<0.001$). Higher levels of seedlings were observed in scarify & rake (SR) treatments in comparison to no preparation (NP) or herbicide application (HA). Within SR, there were more seedlings observed in IS or SA than NS ($P<0.01$). Overall, SA x SR had the most number of seedlings establish ($P<0.01$). Substantial loss of seedlings occurred after emergence but variations across treatments present during germination were evident at 6 weeks and 24 weeks after emergence within treatments where young plants survived. At 52 weeks after emergence hardly any young plants survived but SR and HA had marginally more survival where young plants were present ($P<0.01$).

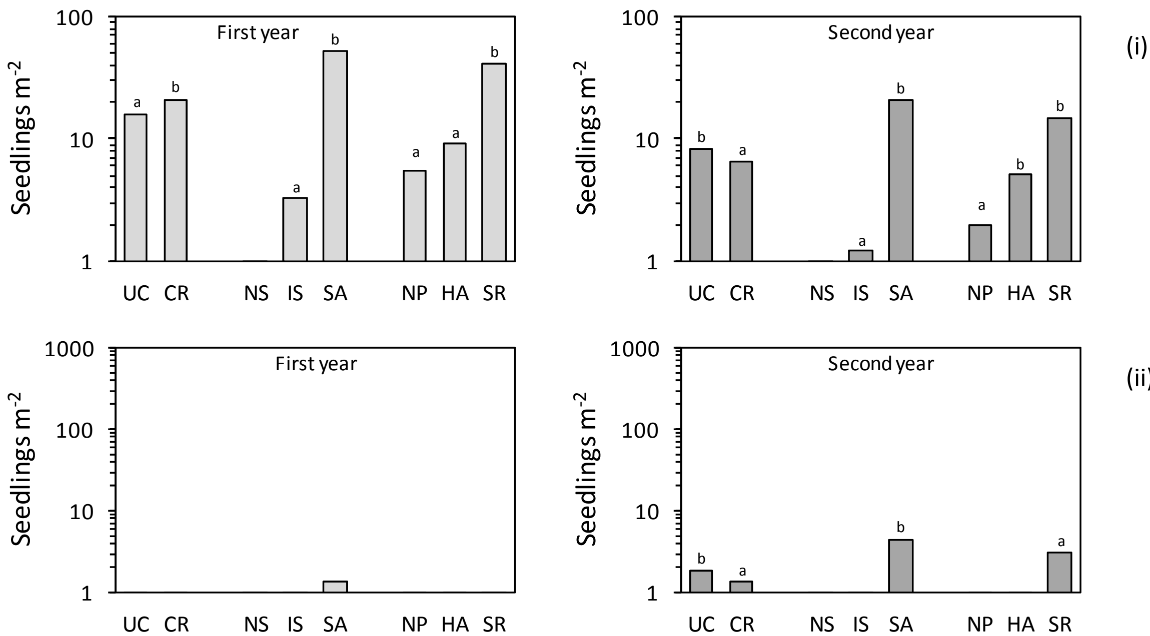

Figure 5. The average number of wallaby grass seedlings m^{-2} (logarithmic scale, n + 1) in (i) March and (ii) 6 weeks after emergence across UC (uncut), CR (cut & remove), NS (no seed), IS (insecticide application), SA (seed addition), NP (no preparation), HA (herbicide application) and SR (scarify & rake) treatments for both first (2007-2008) and second (2008) year experiments; (where the same letter appears on a column within each subset of treatments in the same year, results are not significantly different, P<0.05).

Analysis of factors using multiple regressions indicated seedling numbers were maximised where bare ground was limited (10-15 %), litter high (~0.5 t DM ha^{-1} – only low levels at this site) and green plant material higher (~0.5 t DM ha^{-1}) at emergence. At 24 weeks after emergence, higher plant cover (20-35%) had maximum young plants surviving. Significant relationships were not observed at 52 weeks after emergence though some treatments had few young plants surviving which indicates factors other than microsites (defined by plant cover, litter, bare) and competition (green, functional groups) may be affecting survival.

Wallaby grass recruitment responded in general to leaving swards intact, with positive effects from scarifying and to a lesser extent to sub-lethal applications of herbicide. Maximising seed set is obviously critical as there was a low level of seed set and a generally low density of seedlings.

4.2.2 Second year (2008)

Wallaby grass seedlings were observed in early March (Figure 5) after rainfall during February (95 mm) but in less numbers than the first year experiment. Seed set was less than in the previous year, reflecting the continuing drought. On average 10 seedlings m^{-2} emerged across the site. Similar to the previous year highest seedling number (112 m^{-2}) was observed where the sward was uncut, extra seed added and soil surface layer disturbed through scarify & rake. There was no young plant survival and all emerged seedlings had died by 24 weeks after emergence.

Though substantially less wallaby grass seedlings emerged in the second year, UC recruited slightly more seedlings than CR ($P<0.05$); this was in contrast to the previous year when the reverse applied. Similar to the first year, SA had significantly more seedlings than NS or IS ($P<0.001$), and more seedlings were observed in SR compared to NP or HA ($P<0.001$). IS recruited slightly more seedlings than SA or NS within CR ($P<0.01$); this was not observed in the first year. Across all treatments, SA x SR generated the most number of seedlings ($P<0.01$) the same effect as in the first year.

In general less bare ground (35-50 %) and more green plant material (~0.5 t DM ha^{-1}) maximised seedling numbers at emergence; this range was higher than the first year, possibly reflecting the drier seasonal conditions and greater sensitivity of seedlings to competition that resulted in most dying by early spring.

While the survival of seedlings in this experiment was poor the general indications were that no modifications to the sward structure still seemed to be useful, except that resulting from scarifying at seed maturity. A small effect of insecticide was noted.

4.3 Red grass experiment (Wellington)

Red grass seedlings emerged in early autumn 2007 (Figure 6) after rainfall events in late summer, early autumn (Feb: 31 mm; Mar: 75 mm). The highest seedling number recorded was 279 seedlings m^{-2}, where the plot was pasture cropped, extra seed added and low level herbicide applied. Emerged seedlings gradually declined in numbers and survival rates for young red grass plants were very low. On average, 24 seedlings m^{-2} emerged at the site which decreased to 7 seedlings m^{-2} after 24 weeks after emergence. Young plant survival was tough through the summer conditions and some died but on average 1 young plant m^{-2} was still surviving at 52 weeks after emergence. The pasture cropped plots where extra seed was added and low level herbicide applied had the highest number of young plants (11 m^{-2}) surviving, which also had the highest initial recruitment. Achieving a good initial seed set is important for satisfactory recruitment.

The greater the level of disturbance from ungrazed (UG) to grazed (GR) to pasture cropped (PC) treatments the higher the emergence of red grass seedling numbers ($P<0.05$). PC had substantially higher seedling numbers than UG or GR ($P<0.001$). Emergence of seedlings was significantly increased by seed addition (SA) ($P<0.001$) with few seedlings in no seed addition (NS). More seedlings emerged in herbicide application (HA) than no herbicide application (NH) treatments but this difference was not statistically significant. SA did not have a significant effect within UG but increased seedling numbers significantly within GR and PC ($P<0.001$). SA x PC had the greatest seedling numbers ($P<0.001$). The differences in seedling numbers across treatments remained the same through the period of young plant survival at 6 weeks, 24 weeks though by 52 weeks after emergence seedlings only survived in PC x SA treatments.

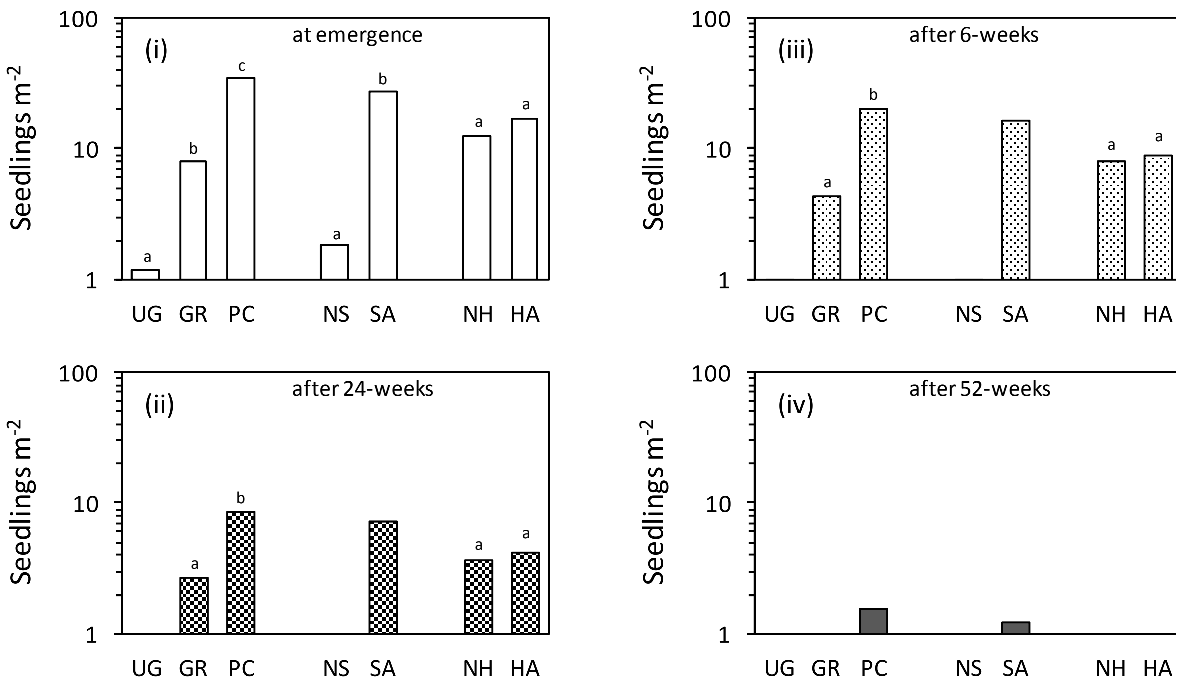

Figure 6. The average number of red grass seedlings m^{-2} (logarithmic scale) in (i) March, (ii) 6 weeks after emergence, (iii) 24 weeks after emergence and (iv) 52 weeks after emergence across UG (ungrazed), GR (grazed), PC (pasture cropped), NS (no seed), SA (seed addition), NH (no herbicide), and HA (herbicide application) treatments; (where the same letter appears on a column within each subset of treatments at each measurement period, results are not significantly different, P<0.05).

In general, the examination of individual relationships from multiple regression indicates that litter DM (~1.4 to 2.2 t ha^{-1}), more bare ground (35-55%) and higher plant cover (45-55%) were associated with maximum numbers of red grass seedlings at emergence. High numbers of seedlings were observed in the bare patches created through PC that had SA but significant relationships between seedling numbers and bare ground within PC were not obtained suggesting presence of seed was a more important factor then bare ground. Use of regression trees across all treatments showed bare ground as the most important factor determining initial seedling numbers (Figure 7). Where bare ground was less than 35% average seedling numbers were 10 m^{-2} (n = 281) and above 35% bare ground had on average 52 m^{-2} (n = 151) seedlings emerging, reflecting competition for moisture at this dry site. At 24 weeks after emergence, plant cover (35%) and less bare ground (10-15%) in general had maximum number of young plants surviving. Regression tree analysis across all treatments though showed bare ground to be the most important factor (as was during initial emergence) in determining overall number of young plants surviving 24 weeks after initial emergence (Figure 8). More than 10% bare ground had on average 14 m^{-2} young plants surviving whereas <10% had only 2 m^{-2} young plants surviving on average.

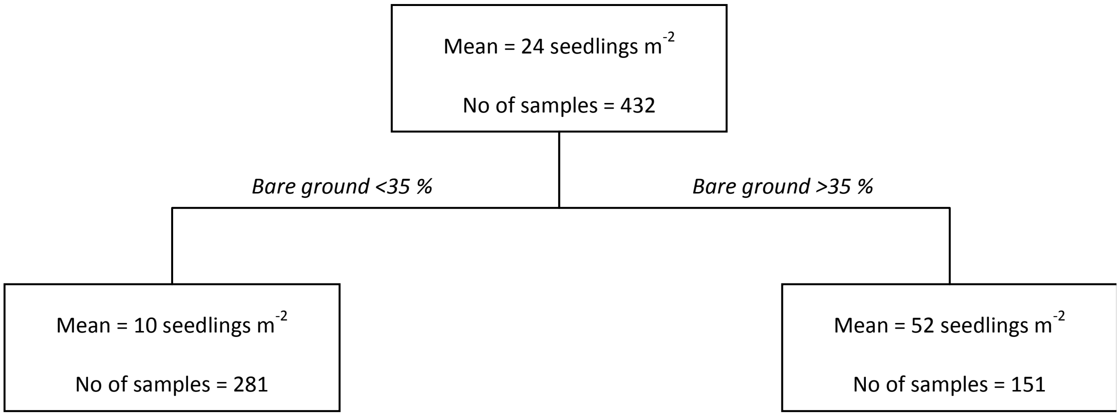

Figure 7. Initial red grass seedling emergence (m^{-2}) in March 2007 as predicted by bare ground (%) across all treatments (standing DM, functional groups DM, green DM, litter DM, bare ground, plant cover were included in the model). Proportional reduction in error (PRE) = 0.105.

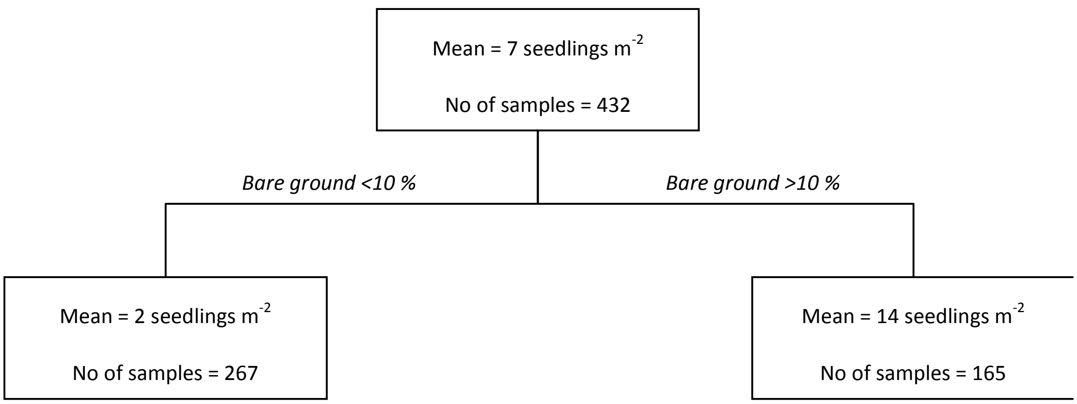

Figure 8. Surviving red grass young plants (m^{-2}) 24 weeks after emergence in August 2007 as predicted by bare ground (%) across all treatments (DM, functional groups DM, green DM, litter DM, bare ground, plant cover were included in the model). Proportional reduction in error (PRE) = 0.09.

The dry nature of this environment meant that more bare ground had a positive influence on recruitment, in association with more litter, but this may in part, be reflecting the pasture cropping treatment which substantially increased recruitment. This suggests that the general result across sites and experiments of no initial modification to swards, apart from scarifying is adequate to enable high recruitment rates. Small positive effects from sub-lethal doses of grass herbicide were found.

4.4 Irrigation experiment

The irrigation experiment was designed to investigate the germinable seed bank in the soil through the year. This was initially done because the dry seasons meant that germination events apart from those noted in the main field experiments, were not being observed. Applying water across the three sites and at six week intervals did not result in any significant seedling recruitment on most occasions even though viable grass seeds were found in the soil cores. The design was then changed to adding viable seed at watering. There were 21 watering events across the three field sites, of which 8 events recorded recruitment: 3 at Orange, 5 at Trunkey Creek and 0 at Wellington. Of the 8 successful recruitment events, 6 had both water and seed applied and coincided with rainfall events. The plots of the irrigation experiments resembled closest the control plots +/- seed addition, of the main field experiments across the sites as no treatments were applied other than water and seed.

At Trunkey Creek 13 seedlings m^{-2} were recorded in mid January 2007 when water was added without seed addition. This event coincided with a rainfall event which extended the period of soil moisture to 10 days and some current mature seed may have been available. A single recruitment event (2 seedlings m^{-2}) occurred in mid September 2007 as a result of the water treatment applied in the end of August 2007 without seed treatment and did not coincide with any rainfall. Limited recruitment (9 seedlings m^{-2}) occurred in early March 2008 with seed addition from a watering event in late February when rain fell shortly afterwards probably making the recruitment possible. This was found similar to the main field experiments – control + seed treatments of the main field experiment averaged 5 seedlings m^{-2}. Trunkey Creek had low recruitment in mid November 2007 and early January 2008 where seed was added and the events coincided with rainfall. The watering treatment in late February 2007 failed to generate any seedlings in early March when rainfall events that coincided with irrigation extended the period of soil moisture to 10 days. The control plots of the main experiments had only 2 seedlings m^{-2} across the site at the same time. It was found *Austrodanthonia* spp. emerged mostly where seed was available and site disturbed through scarifying. The irrigated plots did not have both at the time. The result was similar at Wellington with *B. macra*. The general lack of recruitment in irrigated treatments reinforces the view that native grass recruitment depends predominately on seed availability, increasing the available microsites and adequate soil moisture conditions.

At Orange all 3 observed recruitment events in irrigation experiments had seed added and they coincided with rainfall extending the period of soil moisture to 16-23 days. More seedlings (11 m^{-2}) were found in early March 2008 from the watering treatment in late February. The watering treatment that coincided with rainfall events in late February 2007 did not result in any recruitment whereas the control plots of the main experiments had 16 seedlings m^{-2} at the same time. The irrigation treatment only had half the herbage mass DM t ha^{-1} compared to the control plots of the main experiments at that time. More *P. aquatica* seedlings were found to be associated with higher standing herbage mass.

The irrigation treatments provided estimates of soil moisture conditions that did not result in recruitment or enabled some recruitment. Irrigation may have resulted in priming of seeds, but without follow-up rainfall that did not lead to recruitment. Estimates of surface soil moisture conditions in the irrigation treatments (50 mm over 2 days) showed in most instances when watering did not coincide with any rainfall, the soil (0-50 mm) was moist for only ~5 days. When the irrigation did coincide with a rainfall event the soil remained moist for an average of 24 days across the sites and resulted in some recruitment.

4.5 Soil moisture and temperature at recruitment

The five successful recruitment events observed across the three sites occurred after rainfall events in February that in some instances extended in to early March. The average rainfall during the summer, early autumn period for each site is shown in Table 1.

Table 1. Average long-term rainfall (mm) across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*); annual average along with the monthly averages for December to March presented.

Site	Annual	December	January	February	March
Orange	890	72	88	80	50
Trunkey Creek	800	66	87	62	50
Wellington	620	51	64	60	50

Mean soil and air temperatures at each site during each of the successful recruitment events averaged around 20°C (Table 2). This is near the optimum for germination of seeds of C3 species and where C4 species have a high germination rate.

Table 2. Mean air and soil temperatures (at 50 mm depth) for the periods when soil moisture conditions were considered adequate for the identified successful recruitment events across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*).

Recruitment event	Period	Mean temperature (˚C)	
		Soil	Air
Phalaris aquatica 2006	15 Feb - 6 Mar 2006	17	21
Phalaris aquatica 2007	23 Feb - 12 Mar 2007	22	24
Austrodanthonia 2007	18 Feb - 2 Mar 2007	23	24
Austrodanthonia 2008	1 Feb - 15 Feb 2008	20	23
Bothriochloa macra 2007	27 Feb - 13 Mar 2007	26	31

Soil moisture levels in the top 50 mm were estimated during those successful recruitment events using the SGS model. After initial modelling of soil moisture conditions and reviewing the associated recruitment events it was decided to identify the periods where the soil moisture content was between field capacity (~40% v/v) where free water is available for a seedling to develop, and the permanent wilting point (~20% v/v) where there would be little available moisture for a developing seedling. While actual values for field capacity and permanent wilting points may not be exactly at these points, they were close enough to estimate how long the soil arguably had some available moisture for seedling growth. Some flexibility was used in interpreting the data; for example, if the estimated soil moisture was above and near 20% and then not changing that suggested it was very close to the permanent wilting point and plants would be unable to readily extract more water. In those cases the soil was then considered effectively dry for seedling growth.

In general across the sites there were 2 close rainfall events in the February-March period which increased the soil moisture in the top 50 mm closer to field capacity and these rainfall events preceded the identified recruitment events in March. The soil moisture estimates showed these two rainfall events were usually separated by a maximum of 2 dry soil days. Since sampling for recruitment observations was done after the second rainfall event and daily measurements of recruitment were not taken, it is not possible to say if there was any death of seedlings during these apparently drier days between the 2 rainfall events in the February-March period. Of these two events, the first event could prime the seeds for initial emergence and then the second event established the seedlings or as the first event often provided 5+ days of moist soil, at a time when temperatures were near optimal, the radicle could have actually grown deeper than 5cms in that period and was accessing moisture from a deeper layer. Further work would be needed to evaluate the mechanism. For the purposes of this study the total of these 2 events were considered as the significant rainfall event that enabled seedling recruitment.

The five recruitment events recorded across the five experiments had reasonably common outcomes. Differences between species (one C4 and two C3 grasses) were neither apparent in the timing of the recruitment event, nor in the general climatic conditions under which it occurred. Successful recruitment (Table 3) occurred when the rainfall event (average of 73 mm across the three sites, range 57-99 mm) kept the soil (0-50 mm) moist for a minimum of 14 days, allowing for a maximum of 2 dry days in the period. This event on average, started in mid-February, and often extended to early March, when mature, germinable seed was present. This amount of rainfall for the month of February is just above the long-term average for that month at Trunkey Creek and Wellington but less than the combined rainfall for February and March in all cases. Through those months there is often only one main rainfall event. Future research may show that the average February rainfall (62 and 60 mm at Trunkey Creek and Wellington respectively) may be adequate for a successful recruitment event to occur. Further analyses are needed, but the critical requirement is likely to be the number of rain days above some threshold, rather than total rainfall *per se*. In this study on average, for each rain day there were two moist soil days at the time of the recruitment event, which suggests (based on the range in the data) that 8-14 mm per rain day would be the minimum required, spread through the 7 rain days during the total rain event of 11 days. Successful recruitment occurred from the first significant rainfall event after seed was mature. This event could in practice occur through February until late March. After that period, a greater germination of competitive annual grasses could be anticipated. The parameters derived from these analyses then set the main boundaries to determine the frequency of achieving a successful recruitment event.

The climatic analysis could not be extended to the conditions required through the following summer for plant survival due to low numbers of young plants surviving. Climate records over the months of December and January (Table 4) showed rainfall was below average in most cases and average maximum temperatures were around 24-30˚C. Dry periods of 20-30 days still enabled some seedlings to survive, though only low numbers did as these summers proved generally dry.

Orange had the longest single dry period of 72 days (summer 2006-7) that resulted in no survival of young plants.

The irrigation treatments (50 mm) applied over two days in shaded plots, across the three sites at six week intervals did not result in any significant seedling recruitment on most occasions even though some viable grass seeds were found in the soil cores. There were 21 irrigation treatments across the three field sites, of which 8 events recorded recruitment: 3 at Orange, 5 at Trunkey Creek and 0 at Wellington. Of the successful recruitment events, 6 had both water and seed applied and coincided with rainfall. The two events where recruitment occurred from irrigation without rainfall, only recorded 2 seedlings m^{-2}. Estimates of the number of days where the soil was moist from irrigation, but where no rain fell and there was no recruitment, averaged up to 6 days. Where some recruitment occurred from irrigation, seed addition and rainfall, there was at least 10 days of moist soil. The irrigation treatments were equivalent to the control treatments in the main experiments +/- seed addition, though they often had less herbage mass than shown in the field experiments maximised recruitment. In retrospect this meant that only a low level of recruitment could be expected. These treatments did though suggest that at least 7 days of moist soil was probably needed to obtain some minimal recruitment.

Table 3. Rainfall events in the February-March period that kept the soil in the top 5 cm moist (~40-20%) and probably resulted in the adequate soil moisture conditions for the recruitment event to occur at each experimental site in Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia* spp.) and Wellington (*Bothriochloa macra*); soil moisture data generated from SGS pasture model. Seedling recruitment is the mean for the whole experiment. Percent vol is the range in estimated soil moisture predicted by the SGS model.

Species	**Recruitment event**			**Rainfall**				**Soil moisture conditions**		
	year	date	(seedlings m^{-2})	event	mm	date	rain days	% vol (0-50 mm)	date	moist days
Phalaris aquatica	2006	7 Mar	222	1	33	15 - 18 Feb	3	43 - 24	15 - 23 Feb	9
				2	24	26 - 27 Feb	2	42 - 21	26 Feb - 6 Mar	9
				Total	*57*	*15 - 27 Feb*	*5*	*43 - 21*	*15 Feb - 6 Mar*	*18*
	2007	21 Mar	28	1	54	23 Feb - 1 Mar	6	47 - 23	23 Feb - 3 Mar	8
				2	45	5 - 9 Mar	5	43 - 21	5 - 12 Mar	8
				Total	*99*	*23 Feb- 9 Mar*	*11*	*47 - 21*	*23 Feb - 12 Mar*	*16*
Austrodanthonia spp.	2007	13 Mar	24	1	35	18 - 21 Feb	4	38 - 20	18 - 23 Feb	6
				2	33	26 - 28 Feb	3	43 - 20	26 Feb - 2 Mar	5
				Total	*68*	*18 - 28 Feb*	*7*	*38 - 19*	*18 Feb - 2 Mar*	*11*
	2008	10 Mar	10	1	59	1 - 8 Feb	3	44 - 23	1 - 9 Feb	9
				2	18	12 - 13 Feb	2	34 - 18	12 - 15 Feb	4
				Total	*77*	*1 - 13 Feb*	*5*	*44 - 18*	*1 - 15 Feb*	*13*
Bothriochloa macra	2007	14 Mar	25	1	32	26 Feb - 1 Mar	4	34 - 20	27 Feb - 4 Mar	6
				2	33	5 - 8 Mar	3	41 - 18	6 - 13 Mar	8
				Total	*65*	*26 Feb - 8 Mar*	*7*	*34 - 18*	*26 Feb - 13 Mar*	*14*
Average for total of each recruitment event					**73**	17 Feb – 28 Feb	**7**	**~ 40 - 20**	17 Feb – 4 Mar	**14**

Table 4. Rainfall (mm), the longest dry period estimated by soil moisture in the top 50 cm over the December-January period, mean temperature over that period and average young plant survival (all treatments) at 52 weeks after emergence during the experiments across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*).

Site	**Month**	**Rainfall (mm)**	**Longest dry period**	**Mean temp (°C)**	**Survival at 52 weeks (seedlings m^{-2})**
Orange	Dec 06	16	11 Nov 06 - 24 Jan 07 (72 days)	19	0
	Jan 07	54			
	Dec 07	140	30 Dec 07 - 18 Jan 08 (20 days)	21	4
	Jan 08	55			
Trunkey Creek	Dec 07	35	28 Dec 07 - 18 Jan 08 (22 days)	30	1
	Jan 08	39			
Wellington	Dec 07	148	1 Jan - 30 Jan 08 (30 days)	24	1
	Jan 08	16			

4.6 Past climate data and estimated frequency of recruitment

The results from the climate analysis at recruitment discussed above were then used to analyse the last 30 years of climate data for each study site to determine the probability of successful recruitment events. The SGS model was used to determine for each rainfall event the number of moist soil days that resulted – allowing up to 2 dry days between close rainfall events. The minimal conditions for recruitment were considered to be 7 days of moist soil and the optimum 15 days. It is anticipated over that range seedling recruitment would range from minimal to maximum. Above 15 days of moist soil recruitment would probably still occur but the seedling densities may not increase. Analyses were confined to the period from February 1st until March 31st to cover the period when the current seed set should be mature and the aim was to identify the initial period after maturity when recruitment was possible. Rainfall effects after recruitment were not considered as in each of the five experiments seedlings that established from the first recruitment event survived through to winter when more regular rainfall then occurred. No consideration was taken of small early rainfall events that may affect subsequent recruitment as this research was unable to detect any such effects.

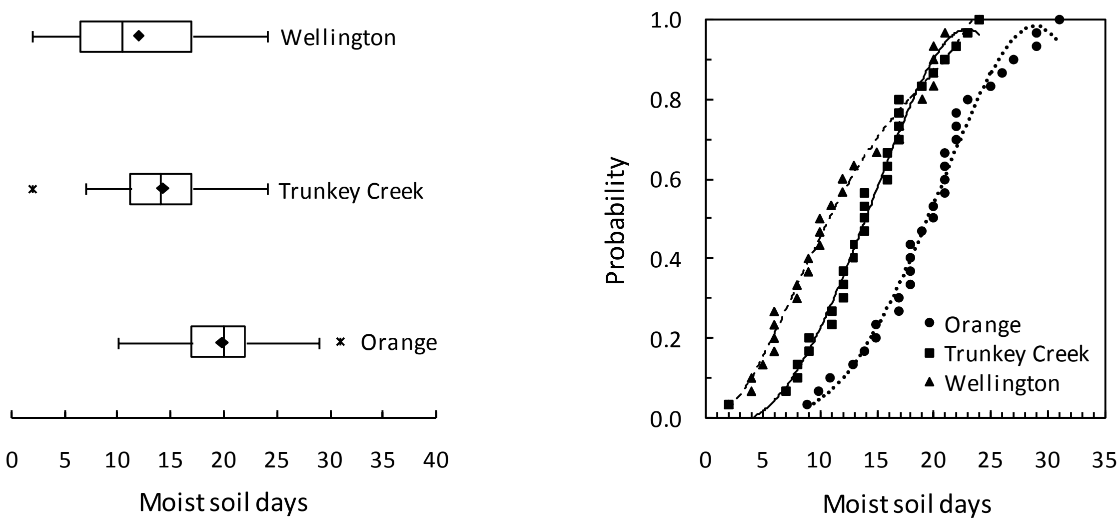

Figure 9. Number of days when the soil was moist in the top 50 mm after a significant rainfall event in the February-March period shown as box plots with average values (as diamonds) and outliers (asterisks) and their probability distribution over the last 30 years across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*).

In the past 30 years, these analyses showed that Orange had an average of 20 moist days each year following a satisfactory rainfall event in the February-March period, whereas it was 14 days for Trunkey Creek and 12 days for Wellington (summarised in Figure 9). On average some recruitment is then possible. The shortest moist period was 2 days at both Trunkey Creek and Wellington, and 10 days at Orange. The longest moist period was 31 days at Orange and 24 days at Trunkey Creek and Wellington.

Further analysis from modelling 30 years of data showed Orange should get some recruitment every year as the probability of exceeding 7 days of moist soil was 98% and 80% of years exceeded 14 days (Figure 9; Table 5). Trunkey Creek would only fail in 10% of years to achieve the minimum moisture conditions of 7 days and 45% of years should have a high chance of recruitment. The site with the lowest probability was at Wellington where still 70% of years would result in some recruitment, but only 33% of year experiencing at least 14 days of moist soil.

Analysis of these longer-term data showed that the average rainfall coinciding with the median days of soil remaining moist for 14 days was 72 mm for Orange but only 44 and 47 mm for Trunkey Creek and Wellington respectively (Figure 10; Table 5) though in each case there was considerable variation. These values are less than identified from the experiments of 57-99 mm. This reinforces the point that the number of days of moist soil and probably rain days above a threshold, are the more important criteria which determine the success or failure of a recruitment event. All sites showed a curvilinear relationship between days of moist soil from the associated rainfall event. This suggests that larger rainfall events tended to have more intense rainfall that did not add greatly to soil moisture and, or the rain fell over shorter time periods. This effect was most noticeable at Trunkey Creek (Figure 10).

Table 5. Median days of moisture for recruitment in the top 5cm of soil and probability of exceeding the minimum and optimal soil moisture conditions of 7 and 15 days respectively and the average rainfall coinciding with the median, 7 and 15 days of moist soil over the last 30 years across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*); estimates are derived from probability distributions in Figure 9 and rainfall versus moist soil days in Figure 10.

Site	Median (days)	Probability of exceeding (%)		Rainfall at (mm)		
		7 days	15 days	median days	7 days	15 days
Orange	20.0	98	78	72	20	48
Trunkey Creek	14.0	92	44	44	20	48
Wellington	10.5	72	30	47	30	80

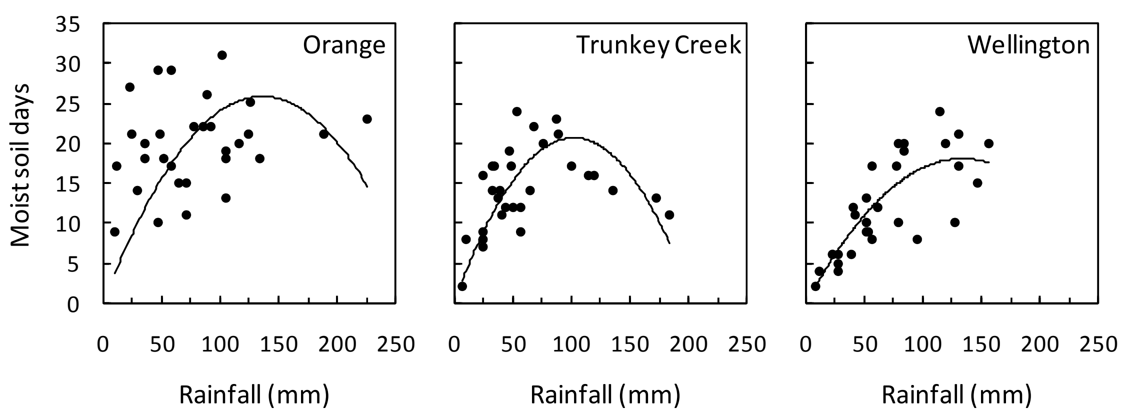

Figure 10. Rainfall events in the February-March period and the corresponding estimated number of days of moist soil in the top 50 mm due to that particular event over the last 30 years across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*). Quadratic curves fitted to the data to show trends.

Estimates of the first significant rainfall event after seed maturity, from 1st February over the last 30 years that would keep the soil moist in the top 50 mm, showed Orange was the earliest in achieving this event, usually in the second week of February. Trunkey Creek and Wellington typically experienced the preferred rainfall event by late February (Figure 11). As Trunkey Creek and Wellington are hotter climates than Orange this meant that temperatures were similar at all sites during the moist soil periods. In some years the first significant rainfall of the year did not occur until later in March. Such events could still prove successful for recruitment as temperatures at this time are still close to 20C, though more competition from annual grasses might then occur. These analyses did not extend into April as often weed competition is more prevalent at that time.

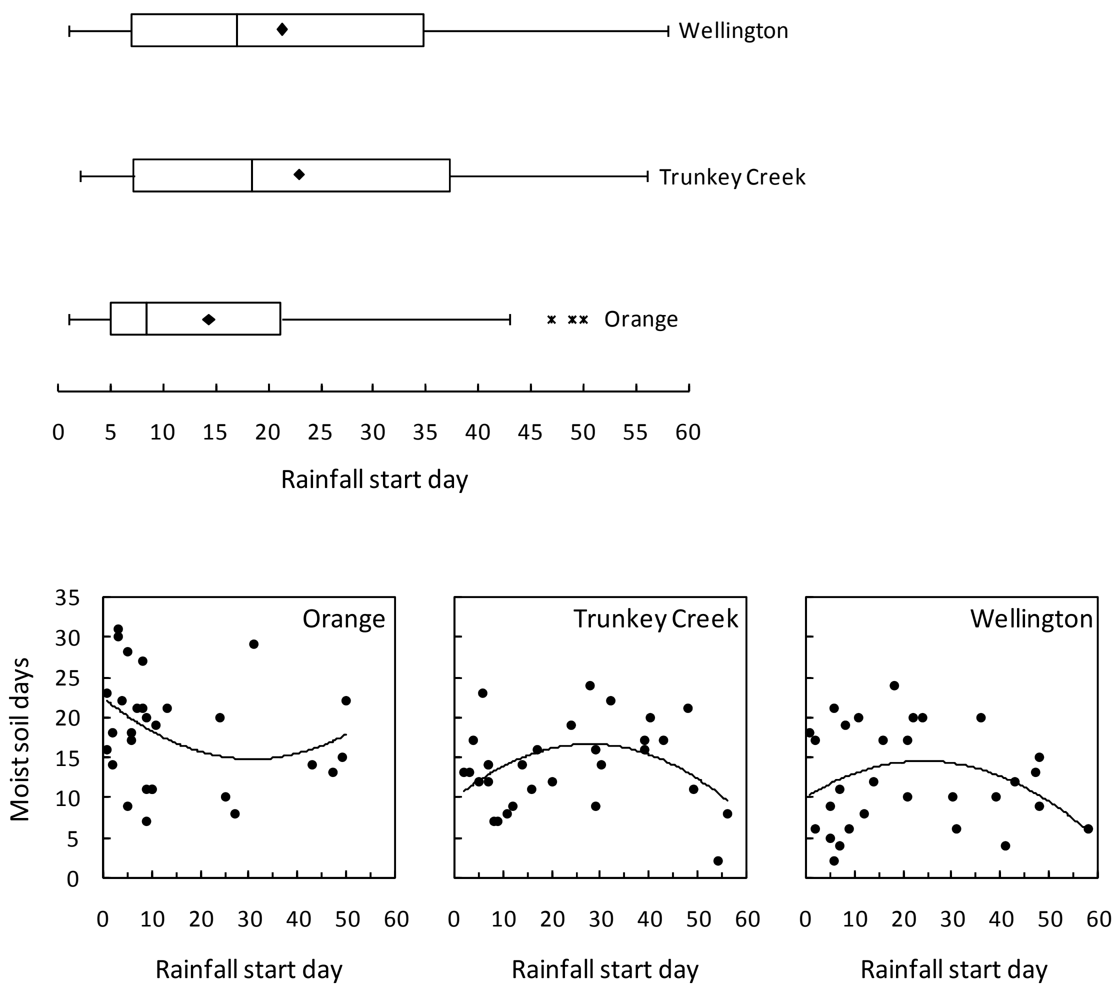

Figure 11. The first significant rainfall event after seed maturity starting from 1st February (denoted as rainfall start day 1) until 31st March (day 59) shown as box plots with average values (as diamonds) and outliers (asterisks) and a series of graphs against the corresponding number of days of moist soil in the top 50 mm due to that particular event over the last 30 years across the three field sites at Orange (*Phalaris aquatica*), Trunkey Creek (*Austrodanthonia*) and Wellington (*Bothriochloa macra*). Quadratic curves fitted to show trends.

The analyses of 30 years of climate data supported the experiment results that there is a respectable probability of adequate rainfall events, usually starting in February each year that would result in a successful recruitment event. Any average or above average years should result in recruitment in paddocks rested from spring to maximise flowering and seed set and on appropriate soils where a light scarifying was done to increase the microsites for recruitment.

5 Discussion

Studies in Australia that reported observations of seedling recruitment of sown temperate perennial grasses (Lodge, 1981; Dowling, *et al*., 1996b; Waller *et al*., 1999; Virgona and Bowcher, 2000; Lodge, 2002a; 2004) had suggested that a successful recruitment event in perennial grasslands is infrequent. However, enabling recruitment of seedlings of desirable perennial grasses within existing swards is shown by these results to be a viable practice that farmers can employ. Despite drought conditions seedlings did successfully establish at all sites in each year of this study. Some seedlings managed to survive through to the next autumn, though it was not possible to adequately investigate the sward conditions that enhanced seedling survival through the first year. Considerable experience is though available on the initial management of sown pastures through the first year after sowing. That information is available to farmers. The larger unknown that this project has addressed is the management of seedling recruitment within existing swards.

5.1 Principles

The consistency in results across five experiments, involving three different species and sites, does enable a common approach to be adopted by farmers in managing recruitment. Further work in this field will undoubtedly identify additional factors to be considered, but the evident consistency with C3 and C4 species across three sites is adequate to develop recommendations for farmers.

The general results across species and sites all indicate that resting paddocks to maximise flowering and seed set creates sward conditions that then resulted in higher recruitment rates. This suggested that vertical litter was more useful than ‘cut and leave’ treatments designed to retain the same biomass but where the ‘litter’ was then in a horizontal position. It is possible that vertical litter increases the boundary layer resistance that then reduces evaporative demand and hence less moisture stress on emerging seedlings. This effect is less with horizontal litter. Attempts to replicate these circumstances in the glasshouse failed (results not presented here) possibly because the effects are subtle (a marginal reduction in stress on seedlings that translates into better survival) and depend upon microclimatic conditions in the field. Litter was still important, but it may be that having a 3 dimensional sward structure is the key to enhanced recruitment. Across the experiments, higher seedling numbers were often associated with more herbage mass and plant cover, except in drier conditions where competition for moisture would be intense and more bare ground proved important. In those drier conditions scarifying treatments proved important and achieved suitable levels of bare ground.

The benefit of soil disturbance on recruitment was variable across sites. With the native grasses some scarifying of sites enhanced recruitment. This might relate to species, but in those cases the soils involved were prone to having gleyed surfaces, which would minimise the physical microsites where a seedling could lodge and germinate. It was considered that this was probably more of a soil than species effect. For experiment purposes soils were scarified with a garden rake i.e. a light implement that mainly scratched the soil surface and did remove some litter and a few small plants. In practice on farms this could be done with harrows of a light scarifying implement that could be dragged behind a 4WD vehicle.

In addition to maximising herbage mass to maximise seed set, then scarifying soils that are not self-mulching, both insecticide and herbicide treatments had some benefits. These effects were variable and while there may be instances where use of insecticide and, or herbicide is justified, those instances are probably narrowly defined. Phalaris is well known as being favoured by seed-harvesting ants and if they are a problem then some control may be warranted. This would particularly apply in average or dry years, where seed set may not be the greatest and competition from ants more intense. However as shown in this project, treatments without insecticide still had useful seedling densities. In wetter years seed production may exceed the capacity of ants to remove them all and as a result they are of less concern. Insecticide benefits for the native grasses were less clear, but would warrant further study to understand predation rates.

Low-dose grass-specific herbicide applications were used at seed maturity to see if that lessened competition from mature plants and, or killed any annual grass seedlings that were present. The effects of this herbicide treatment on recruitment were generally small. That probably reflected dry seasonal conditions being a larger constraint on the competitiveness of other grasses. In these experiments annual grasses were anticipated as a problem, but in the event were only a minor component of each pasture. However it is known that annual grasses are often a serious competitive problem for perennial grass seedlings. Annual grasses often have larger seedlings and, or higher seedling densities than perennial species. The treatment employed in this project did show that grass herbicides can be successfully used without damaging in any noticeable way the mature plants of desirable species, nor have any effects that influenced the germination and recruitment of perennial grass seedlings. Farmers who find there is an annual grass problem could trial the herbicide treatment used here. This circumstance might only occur in rare seasons where annual grasses were germinating before the main recruitment event for perennial grasses. It would seem that the need for insecticide or herbicide applications could be rare. Herbicides for broadleaf weed control are a simpler practice and can then be used if a significant problem emerges. In much of the landscape where native grasses occur, competition from weeds, at the time when recruitment occurred, may not be a major difficulty.

The rainfall event that triggered successful recruitment at each experiment and site was typically in late summer, early autumn and resulted in ~15 days where there was moisture in the top 5cms of soil. These events were successful even when there were two dry days in the middle of this moist period. As soil temperatures were around 20°C seedling growth rates were probably high and the radicle may have been accessing deeper soil moisture by the time those drier days arrived. A moist period of <7days was not adequate for successful recruitment. Seedlings may have emerged from those events, but none were detected when counts were taken 2-3 weeks after the rainfall, or irrigation events. The modelling work has indicated a high probability of obtaining a 7 day moist soil event around the appropriate time in late summer, autumn at each of the sites studied, while a 15 day moist soil event is of lower probability. The tablelands sites (Orange and Trunkey Creek) would probably expect some recruitment in most years, the site on the slopes (Wellington) have a lower probability, but still have a 30% chance of achieving 15 moist soil days. The median moist soil days at Wellington found from analysing 30 years of rainfall data was ~10 days, which could be expected to result in some recruitment in at least 50% of years.

5.2 Seed dormancy and seed banks?

The field experiments consistently showed one major recruitment event each year at each site. Observations of those experiments through the year failed to identify any other significant germination events. The irrigation experiment, across all sites, similarly found few seedlings emerging at other times. This general result has been perplexing as the native grass seeds in particular, are known to have a dormancy period after maturation and the expectation that there is a soil seed bank. Phalaris has been selected as a cultivar with minimal dormancy. The soil cores taken through the year and tested for readily germinable seed, found few perennial grass seedlings emerging. Other studies (King *et al.*, 2006) at the Carcoar SGS site found almost no perennial grass seedlings emerging from cores kept in a glasshouse for a year. Previous research has shown that seed banks of perennial grasses are usually at low levels in the soil (Virgona and Bowcher, 1998; Lodge, 2001; 2004) even though the amount of seed produced is often high (Lodge, 2004; Kelman and Culvenor, 2007). There are many studies (Winkworth, 1971; Eberlein, 1987; Chambers, 1989; Silcock and Smith, 1990; Silcock *et al*, 1990; Anderson *et al*., 1996) that claim that the seed of many grass species remains viable in the soil for as little as two years. These collective results all support the view that natural recruitment rates would be low outside the ‘window of opportunity’ found around February, March soon after seed is produced.

The role of dormancy in these species is then unclear, though tests of these species show that a high proportion of the seeds were dormant (J Stevens, unpublished data). From this project the general conclusion though is that there is only one main recruitment event for these species each year and that is the first significant rainfall event after seeds mature. If a large proportion of that seed is dormant then that means recruitment will often be seed limited and all other factors need to be optimal to maximise recruitment. Little reliance can be placed on soil seed banks, current seed set is critical. In the future it may be possible to apply chemicals to seed in the paddock to break dormancy and maximise the seed available for seedling recruitment.

5.3 Where will the technology developed work?

Enabling the recruitment of perennial grasses should then be possible in regions in south-eastern Australia that are characterised by occasional but significant rainfall events in late summer / autumn. Often after the event that enabled seedling recruitment, there was little rain for the subsequent 2-3 months, yet a reasonable number of seedlings survived, indicating that continuing rainfall through autumn is not essential. If high numbers of seedlings are initially established then enough will survive through to spring to achieve the goal of increased perennial grass densities if rainfall is about or above average (not drought as occurred in this project). In south-eastern Australia the Northern Tablelands of NSW are characterised by summer rainfall that changes to an autumn, winter pattern further south. The Central Tablelands and nearby slopes get some summer rain, but this is often only 2 or so events each year. On the Central Tablelands the start of more frequent rainfall periods is often not until late May. Further south less frequent summer rain is the norm, but the start of more regular rainfall occurs progressively earlier e.g. early March in some districts. These patterns plus the fact that the species studied in this project naturally occur in southern regions i.e. they do recruit new plants at some time, suggest that the rainfall patterns experienced in the higher rainfall zones across south-eastern Australia are suitable for encouraging perennial grass recruitment. The key climatic requirement would be that rain falls when soil temperatures are ~20C, which results in faster growth of seedlings and less recruitment of weeds such as annual grasses. If temperatures are less a longer period of moist soil would be required to enable recruitment. Further work though is needed to clarify where the results presented in this project would apply and if the same principles work with other important grasses (*Themeda australis*, *Microlaena stipoides*). The methods presented on climate analysis can be used to identify the regions where there is a reasonable chance of encouraging recruitment.

5.4 Threshold analyses

This work has found that analyses done using regression trees offer useful insights into the criteria that can be used to judge success of treatments and to develop improved guidelines for management. All potentially important factors were included in each regression tree analysis, but only some were statistically significant and those factors are then ranked in importance within the tree. Previously studies such as this one typically sought response relationships, but the inherent variability in much field data, where many factors interact, make it difficult to detect the underlying response curves. The attractiveness of regression trees is that they provide a threshold analysis either side of which system costs or benefits are apparent. For example in the case of phalaris, if the herbage mass was >3.9 t DM ha^{-1} at the recruitment event in 2006, then the average seedling density was 521 *cf* 111 for plots below that threshold. Then for swards above the herbage mass threshold with >45% plant cover, the average was 804 seedlings m^{-2} compared with 404 seedlings m^{-2} if <45%. In 2007 under drier conditions the threshold herbage mass was 2.7 t DM ha^{-1}. Collectively these results suggest that if the herbage mass in late summer is ~3 t DM ha^{-1} then recruitment would be enhanced. This effectively translates directly into useful recommendations to farmers of targets for herbage mass and plant cover which should maximise recruitment. It does not define optimal conditions, but in practice managing to an optimum would not be possible in the landscapes under study. The previous approach of defining response curves, while being difficult in practice to identify, also defines an optimal condition to manage for that is close to non-limiting e.g. at 95% of the maximum response. Threshold targets for management derived from regression trees would be mostly below the optimum, but they are arguably more realistic for farmers to manage to and in effect could prove to be closer to the economic optimum in many instances. Threshold analyses were used in defining some of the parameters incorporated into the decision chart.

5.5 Decision chart

Based on the general results from the three experimental sites at Orange, Trunkey Creek and Wellington, a decision support chart (Figure 12; Appendix 10.2) was developed to summarise the main recommendations from this study. The objective of this tool is to provide farmers and their advisors with a simplified strategy for pasture management that enables them to encourage recruitment of desirable perennial grasses.

The starting step is during spring to select a paddock where there is a need to increase the perennial grass content. When first using the techniques developed in this project, select paddocks where the perennial grass content is around 30% and without major weed problems. This would enable farmers to gain experience and see results in a reasonable time. Where major weed problems occur then they would need to be controlled to some extent before implementing this strategy. If there is less than 20% perennial grasses, the opportunity to enhance the perennial grass content is arguably low and other actions e.g. some weed control so that any seed produced is mostly from desirable grass species, may be needed to bring the paddock to a point where the recommendations presented here could be implemented.

The selected paddock is locked up by late spring to allow plants to flower, set seed and for that seed to mature and fall (*i.e.* summer rest). Seed banks of perennial grasses are usually at low levels in the soil (Virgona and Bowcher, 1998; Lodge, 2001; 2004) which emphasises the need to promote flowering and seed set. Assume that recruitment will depend predominately on current seed set.

Annual grasses and seasonal weeds could be a problem and if the paddock has a known history with these species, control measures need to be used. Weeds did not prove a problem at the field sites, but the sub-lethal grass herbicide treatment did show that the desirable perennial grasses tolerated that treatment and there was no deleterious effect on seedling recruitment. Broadleaf weed control would not pose problems for perennial grass recruitment. In much of the landscape where native grasses are, these short-term weed problems will only be occasional. The more serious problem is serrated tussock (*Nassella trichotoma*) and current recommendations are the spot spray plants to both prevent seed set and to kill adult plants, while minimising collateral damage to desirable species. [See final report on MLA Weed.125 (2009) for current methods for serrated tussock control.]

Seasonal conditions need to be carefully monitored through December and January to decide if the rest is to be continued and if any scarifying or insecticide is needed, or if there is unlikely to be any useful recruitment because of a dry season. Wellington was the driest of all sites; only 40% of average rainfall (*i.e.* 20 percentile) was recorded for the period December 2006-January 2007 which limited plant growth and seed production considerably. To achieve good flowering and seed set, it is suggested that unless 40% of average rainfall is received, the chances of obtaining a good seed set will be limited. If the season is poor (< 40% average rainfall) then the best decision maybe to forego the option of fostering recruitment as the chance of good rain at the right time is reduced, the feed is probably needed for livestock and flowering and seed set will be limited.

If seed harvesting ants are very active and seed set might be low then applying some insecticide before seed fall could be important for phalaris. The benefits of using insecticide on native grasses do not seem large enough to justify the cost.

Presence of suitable microsites when seed is mature around late January is essential and that depends on the characteristics of the soil of the paddock. On self-mulching soils nothing need be done but on other soils a light scarification could enhance recruitment. If the season is dry that has the added advantage of reducing the competition from existing plants, which benefits recruitment.

The conditions where recruitment occurs were found to differ between species. For phalaris the standing swards of 3 t DM ha^{-1} that consisted of less than 50% green DM in late summer resulted in the most seedlings. Bare ground was less important as intact swards with more than 30% plant cover were preferable to enhance recruitment. In contrast bare ground was one of the more important factors in improving recruitment of native grasses. In general presence of 30-50% bare ground was beneficial, arguably reflecting the dry seasons that occurred during this project. In all experiments a low level of litter enhanced recruitment and there seemed to be an upper limit (~1-2 t DM ha^{-1}) above which recruitment declined. The experiments showed the combinations of these factors provided favourable microsite conditions for seedlings to emerge.

The analysis of climatic conditions showed a significant rainfall event in late February / March resulted in adequate soil moisture for seedlings to establish in March. Temperatures were close to optimal for germination of perennial grasses during this period. In general across the sites 15 days of moist soil surface in the top 50 mm, with a maximum of 2 dry days during the moist soil period, was optimal for maximum seedling recruitment. This was associated with an average of 50-80 mm of rain (more at the hotter Wellington site) falling over 7 rain days maintaining the surface soil moisture for those 15 days. Analysis of the last 30 years of rainfall data found that there was a probability of 30-78% across the sites of achieving these optimal conditions. The minimal condition for some recruitment detected in these studies was at least 7 days of moist soil, which had a high probability of 72-98%. These analyses suggest that in most years some recruitment would occur and that if possible farmers rest paddocks from spring through to late March if seasonal conditions permit to maximise the opportunities for recruitment. Further rests would then continue if seedlings had emerged.

The conditions for survival of young plants were not resolved in this study due to low frequency of survival. General observations though suggested competition may be the biggest factor during early stages of survival. Light grazing over 12-52 weeks of emergence is an option once seedlings become robust. The subsequent survival of young plants may depend more on maintaining adequate soil moisture conditions and reducing competition through summer. Guidelines developed for managing sown pastures would be applicable to managing pastures through natural recruitment at this stage in our understanding of these ecosystems.

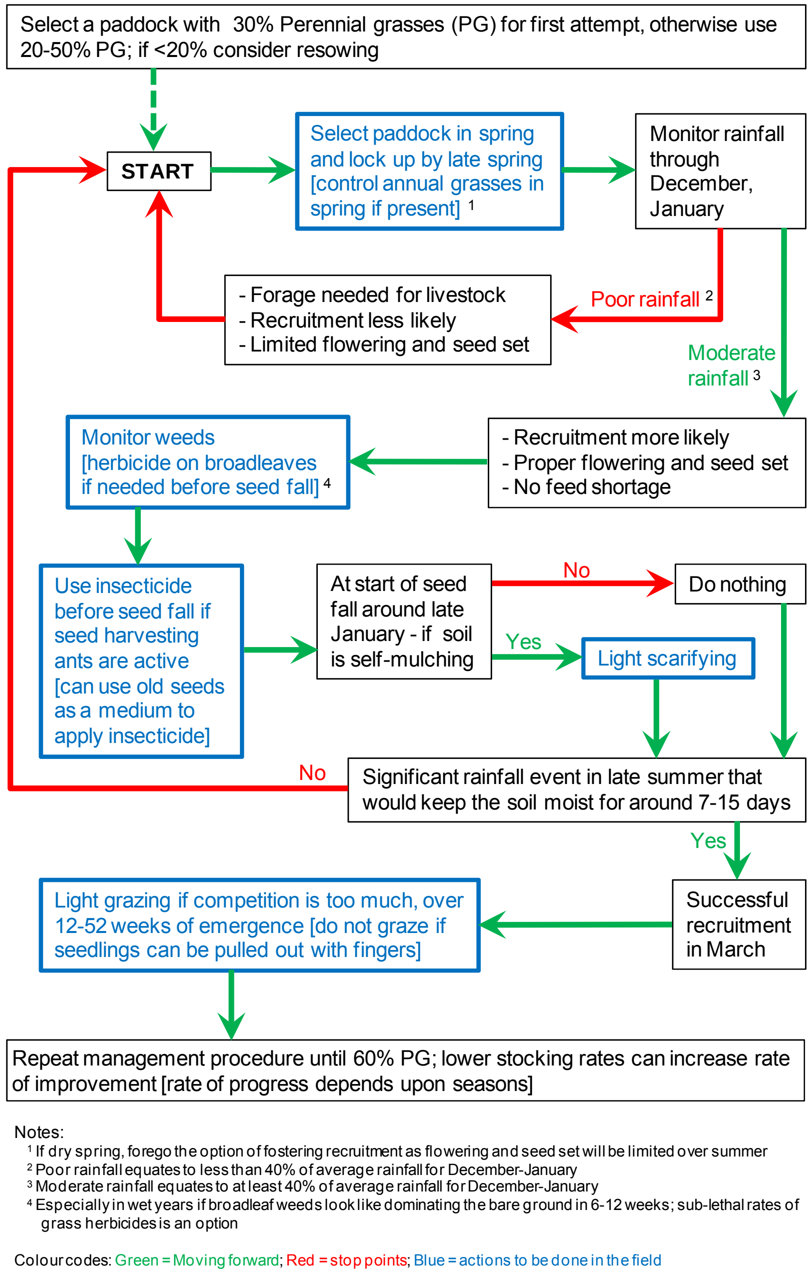

Figure 12. Decision support pathways to enable recruitment of perennial grasses.

6 Success in achieving Objectives

The first project objective to "develop basic information on low-cost management practices to successfully re-establish perennial grass plants within typical native/naturalised grasslands of central New South Wales without resowing", formed the bulk of the project and has been successfully completed. This report outlines the major findings from a series of experiments and analyses. Further details can be found in the PhD thesis (Thapa, 2009). Management practices for enabling recruitment of perennial grasses within existing pastures are now available.

The key components of the second objective to “develop a print ready producer publication on the recommended practices” is summarised in this report and the final copy will be ready later in the year. The scientific work done has been developed into a decision flow chart (Figure 12; Appendix 10.2) with associated guidelines on its use.

The third objective to “run two open days at research field sites providing a research update demonstrating the processes required for low cost rehabilitation of perennial pastures” was not done due to the drought. During the course of the project this was discussed with the MLA Program Manager as the drought meant that there was little to show in the field due to the poor survival rate of seedlings. It was agreed that the field days were not appropriate. Project results have though been presented at seminars and discussed with local advisory staff. Plans are in place to produce extension material and as part of that activity hold wider discussions with relevant groups to ensure that material considers all the likely farmer concerns that could arise. Resting paddocks over summer to encourage recruitment were incorporated in the MLA Serrated Tussock Project (Weed.125) and demonstrated at field days.

7 Impact on Meat and Livestock Industry

7.1 Now

Surveys done over recent years (Kemp and Dowling, 1991) found that the perennial grass content of pastures surveyed was often only 20%, when those species were present. Research done at the Carcoar SGS site (Michalk *et al.* 2003) indicated that at least 60% perennial grass is needed to have useful impacts on livestock production, weed control, lessen acid soil development and better water use to minimise salinity problems. Earlier studies at Newbridge (Kemp *et al.,* 1996) demonstrated that under summer rests the proportion of cocksfoot (*Dactylis glomerata*) in a pasture was increased from 10-50% over 4 years i.e. ~10% *p.a.* That work was unable to provide insight into the mechanism involved, though observations indicated new plants had established. This background when considered with the research presented in this project suggests that a steady improvement in the perennial grass content of average pastures across south-eastern Australia is now possible in a predictable manner.

At present farmers are sowing few new pastures and not providing many inputs e.g. fertiliser, to the existing ones. They are living on their capital, which will probably only decline. The net effect is arguably for stocking rates to decline. However restoring pastures to a more productive state can be done and the research in this project has shown how the core issue that of increasing the perennial grass content, can be managed. This is a critical first step in pasture improvement as demonstrated at the SGS Carcoar site (Michalk *et al.,* 2003). That work showed that improving the botanical composition needs to precede other inputs such as fertiliser. Farmers now have a low-cost approach to pasture improvement for those large parts of the landscape where there are still some desirable perennial grasses and no over-riding weed problems. The restored pasture may not be as productive as a newly sown pasture, but the investment costs are considerably less and hence restored paddocks could prove more profitable.

A conservative rate of improvement in perennial grass content may only be 10% *p.a.* (of the total herbage mass) such that from an average of 20%, it could take 4 years to reach a target of 60%. Costs involved could vary from nil e.g. when resting the paddock without any impact on the forage available for the livestock on the farm, to where inputs are progressively required for light scarifying, insecticide for ant-control and, or herbicide to control weeds. Of the practices identified, scarifying seems to be the main one that could be used at times to create microsites to improve recruitment rates. As discussed earlier, the occasions when insecticide and herbicide are needed could be rare. A light scarifying may only cost \$20 ha^{-1}. This is in contrast to \$300 ha^{-1} to sow a new pasture.

Through the period of fostering recruitment to bringing the perennial grass content to 60% the carrying capacity of a paddock may not change initially. But once the target is reached then either more stock or more production per head would result. On many of the poor native grass areas in NSW it is not unreasonable to anticipate doubling production in the medium term.

7.2 In five years time

As noted above it could take 4-5 years for the perennial grass content of a pasture to be increased to the desired content of 60%. At this point increased livestock production would be greater than for the current degraded state.

Farmers have been adopting rotational grazing practices in increasing numbers for the last 20 years or more, often in direct response to the programs run by MLA and other Agencies (Kemp and Michalk, 1993; Kemp *et al.*, 1996). Many farmers though are not always sure of why they are moving livestock around and of how to vary their grazing practices to help rehabilitate weaker pastures. This project has provided the reasons for when and how long, weaker paddocks can be rested to improve the proportion of desirable perennial grass species. In five years time with the information provided by this project it is anticipated that more farmers will be targeting paddocks for rest periods with better knowledge as to why and for what they need to monitor to improve farm productivity. Rehabilitating paddocks in this way will be of lower cost and can be used to increase the proportion of desirable perennial grasses before applying fertiliser, which otherwise may only stimulate the growth of weed species. Building more ecological practices into day to day farm management will become more common.

8 Conclusions and Recommendations

This research did show that recruitment occurred in the five field experiments done, that minimal intervention was required (rests to maximise seed set, light scarifying on non-self-mulching soils and ant control and herbicide treatments in occasional circumstances) and often only one rainfall event in late summer was needed to produce enough seedlings for a reasonable number to survive through to the next spring.

Key messages:

- The results were similar for all three species studied and common principles were established to enable successful seedling recruitment.
- Current seed set is critical for successful recruitment as there was limited germinable seed in the soil seed bank. Rest paddocks from spring to maximise flowering, seed set and maturity.
- Seed production is low during dry years and hence the numbers of seedlings establishing through those years will be less than could be achieved if extra seed was supplied, but still useful for increasing the perennial grass content if there is sufficient rainfall over the following year.
- Seedling recruitment was greater where there was:
    - more seed set (rest paddocks from spring),
    - more (uncut / ungrazed) herbage mass was present in intact swards,
    - where some soil disturbance (light scarifying) on non self-mulching soils occurred (this did not apply for the phalaris experiment, as in that case the soil was naturally self-mulching),
    - insecticide to control seed-harvesting ants (if a problem as is often the case with phalaris), and
    - herbicide at low rates at seed maturity to weaken plant competition i.e. before recruitment, may help reduce competition in some cases (this would apply if significant weed problems were evident or highly likely).
- The surface soil (top 50mm) needs to be moist for > 7 days and ideally 15 days to enable a high density of perennial grass seedlings to establish. In all five experiments suitable conditions occurred around late February and through March each year, despite the dry seasons. These soil conditions resulted from 50-80mm (more rain needed at the warmer site at Wellington) of rain over several days. Periods of 2 dry surface soil days in a 15 day period did not seem to limit recruitment.
- Analysis of the last 30 years of rainfall at each site found that the minimal requirement of 7 days of adequate surface soil moisture occurred in late summer, early autumn in 98%, 92% and 72% of years at Orange, Trunkey Creek and Wellington, while 15 adequate soil surface moist days occurred in 78%, 44% and 30% of years, respectively. This indicates that useful recruitment would occur in most years.
- Conditions for seedling survival through the following year were not resolved due to the drought. Future work needs to investigate the interaction between plant competition and soil moisture conditions on seedling survival within existing swards.

This work showed that in most years it would be useful for farmers to rest paddocks to enable recruitment if suitable seasonal conditions then followed. Typically the forage for grazing only becomes restrictive to livestock by late summer and autumn. Thus in dry years seedling recruitment and survival is less likely but a rested paddock has then some forage available that can be used. In wet seasons there is usually no shortage of fodder and resting the paddock for longer periods is not a major difficulty. The paddock would be out of use for less time than applies if sown to a pasture. After locking up paddocks they need to be monitored to decide if intervention is needed for scarifying, insecticide or herbicide treatments. Costs would probably be about 10% that of sowing a new pasture. A decision chart has been developed to guide farmers and their advisors in using the information gained in this project.

A consideration of climates throughout south-eastern Australia suggests that the principles developed in this project will apply in many areas. Rainfall events from late summer, through autumn occur in many of those districts. The grasses studies in this project are known to exist throughout the south-east and do naturally recruit. This work suggests that much of that recruitment is probably occurring in late summer and autumn. In different districts some preliminary work would though be needed to determine if the techniques coming from this project need any modification.

Farmers are now in a position to more reliably enable recruitment of desirable perennial grasses within their pastures. The outcomes can be achieving 60% perennial grass at significantly lower-cost, at which improved production and environmental outcomes can be achieved.

This work has identified key management practices that can be used, but there are several areas that need to be considered in future work:

- Wider climatic analyses to resolve the regions across south-eastern Australia where the tactics developed in this project can be used. This would involve analyses of likely soil moisture conditions at the time of the year when recruitment is possible.
- Determine how important seed dormancy actually is for native grass recruitment. It may be that dormancy is limiting the number of viable seeds available for recruitment and that predation removes many of those seeds before they can germinate. Field work is needed to investigate the use of dormancy breaking chemicals to maximise recruitment rates.
- Develop practices to maximise seedling survival through the year after emergence. This would require field work on the level of plant competition from desirable species and weeds, and grazing that seedlings can tolerate and the amount of plant material that helps protect the young plants.

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10 Appendices

10.1 Seedling stage definitions

Stages identified in the recruitment process and the working definition used for each stage.

Stage A: Seedling recruitment: The early stage process that involves germination, seedling emergence and seedling establishment. New plants are recruited to the population though they may or may not survive subsequently. From a practical perspective this whole sequence is considered to take approximately 6 weeks after germination first starts as not all seeds germinate at exactly the same time and seedlings need to reach a certain stage of development - as defined below.

i. Germination: Any seed is considered to have germinated when the embryo emerges (generally radicle first then the shoot) through the seedcoat or testa. This happens when a viable (*i.e.* living) seed is wetted, water is imbibed, respiration, protein synthesis and other metabolic activities begin (Bewley and Black, 1978) and growth commences. This stage is difficult to observe within existing swards.

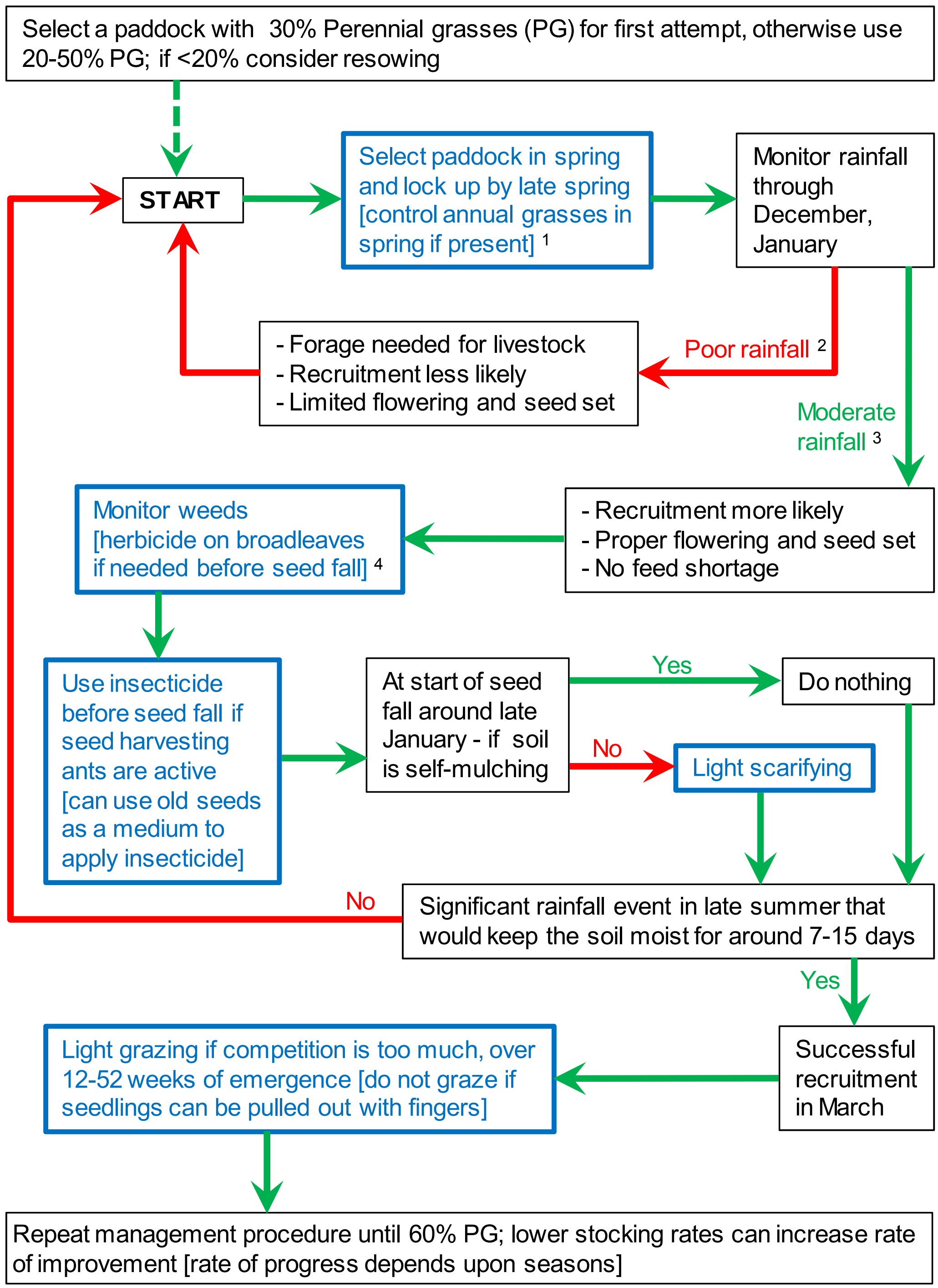
ii. Emergence: The protrusion of the primary root through the coleorhiza and the first leaf through the coleoptile marks the successful emergence of a grass seedling (Bewley and Black, 1978). This usually is the first change noticed in the field and generally occurs 1-2 weeks after a substantial rainfall event.

iii. Seedling establishment: The stage at which a seedling becomes photosynthetically active and independent of seed reserves, when the cotyledons have fulfilled their function and when at least two new leaves have emerged. This stage is difficult to measure and is dependent upon environmental conditions (Jackson and Jacobs, 1985), but is when the seedling becomes a recognisable plant.

Stage B: Young plant survival (medium-term): The period from around 6 weeks after germination, and through the seedling recruitment phase to the end of the first entire summer after germination. This phase brings plants to the stage where they would be capable of completing their life cycle (*i.e.* flowering and seed set) and have survived what is often an intense period of plant competition and climatic stress. In some instances a perennial plant that germinates in autumn can flower that spring if growth conditions are suitable but the better criteria for young plant survival in southern Australia is the endurance through the first summer after initial emergence. This definition is appropriate for farm practice and more extreme than commonly used in agronomic research where establishment success is often judged 2-3 months after germination.

Stage C: Long-term survival: The stage after medium term survival, when the young plant is fully recruited to the population, remains for a long time and there are several opportunities for it to produce progeny. This stage is not considered in this project as the factors that affect long-term survival are likely to be different from those that affect seedling recruitment and young plant survival.

10.2 Decision support pathways to enable recruitment of perennial grasses



Notes:

[1] If dry spring, forego the option of fostering recruitment as flowering and seed set will be limited over summer
[2] Poor rainfall equates to less than 40% of average rainfall for December-January
[3] Moderate rainfall equates to at least 40% of average rainfall for December-January
[4] Especially in wet years if broadleaf weeds look like dominating the bare ground in 6-12 weeks; sub-lethal rates of grass herbicides is an option

Colour codes: Green = Moving forward; Red = stop points; Blue = actions to be done in the field

Guidelines on the use of the decision support chart

1. The starting step is during spring to select a paddock where there is a need to increase the perennial grass content. When first using the techniques developed in this project, select paddocks where the perennial grass content is around 30% and without major weed problems. This would enable farmers to gain experience and see results in a reasonable time. Where major weed problems occur then they would need to be controlled to some extent before implementing this strategy. If there is less than 20% perennial grasses, the opportunity to enhance the perennial grass content is arguably low and other actions e.g. some weed control so that any seed produced is mostly from desirable grass species, may be needed to bring the paddock to a point where the recommendations presented here could be implemented.

2. The selected paddock is locked up by late spring to allow plants to flower, set seed and for that seed to mature and fall (*i.e.* summer rest). Seed banks of perennial grasses are usually at low levels in the soil which emphasises the need to promote flowering and seed set. Assume that recruitment will depend predominately on current seed set.

3. Annual grasses and seasonal weeds could be a problem and if the paddock has a known history with these species, control measures need to be used. Weeds did not prove a problem at the field sites, but the sub-lethal grass herbicide treatment did show that the desirable perennial grasses tolerated that treatment and there was no deleterious effect on seedling recruitment. Broadleaf weed control would not pose problems for perennial grass recruitment. In much of the landscape where native grasses are, these short-term weed problems will only be occasional. The more serious problem is serrated tussock (*Nassella trichotoma*) and current recommendations are the spot spray plants to both prevent seed set and to kill adult plants, while minimising collateral damage to desirable species.

4. Seasonal conditions need to be carefully monitored through December and January to decide if the rest is to be continued and if any scarifying or insecticide is needed, or if there is unlikely to be any useful recruitment because of a dry season. Wellington was the driest of all sites; only 40% of average rainfall (*i.e.* 20 percentile) was recorded for the period December 2006-January 2007 which limited plant growth and seed production considerably. To achieve good flowering and seed set, it is suggested that unless 40% of average rainfall is received, the chances of obtaining a good seed set will be limited. If the season is poor (< 40% average rainfall) then the best decision maybe to forego the option of fostering recruitment as the chance of good rain at the right time is reduced, the feed is probably needed for livestock and flowering and seed set will be limited.

5. If seed harvesting ants are very active and seed set might be low then applying some insecticide before seed fall could be important for phalaris. The benefits of using insecticide on native grasses do not seem large enough to justify the cost.

6. Presence of suitable microsites when seed is mature around late January is essential and that depends on the characteristics of the soil of the paddock. On self-mulching soils nothing need be done but on other soils a light scarification could enhance recruitment. If the season is dry that has the added advantage of reducing the competition from existing plants, which benefits recruitment.

7. The conditions where recruitment occurs were found to differ between species. For phalaris the standing swards of 3 t DM ha^{-1} that consisted of less than 50% green DM in late summer resulted in the most seedlings. Bare ground was less important as intact swards with more than 30% plant cover were preferable to enhance recruitment. In contrast bare ground was one of the more important factors in improving recruitment of native grasses. In general presence of 30-50% bare ground was beneficial, arguably reflecting the dry seasons that occurred during this project. In all experiments a low level of litter enhanced recruitment and there seemed to be an upper limit (~1-2 t DM ha^{-1}) above which recruitment declined. The experiments showed the combinations of these factors provided favourable microsite conditions for seedlings to emerge.

8. The analysis of climatic conditions showed a significant rainfall event in late February / March resulted in adequate soil moisture for seedlings to establish in March. Temperatures were close to optimal for germination of perennial grasses during this period. In general across the sites 15 days of moist soil surface in the top 50 mm, with a maximum of 2 dry days during the moist soil period, was optimal for maximum seedling recruitment. This was associated with an average of 50-80 mm of rain (more at the hotter Wellington site) falling over 7 rain days maintaining the surface soil moisture for those 15 days. Analysis of the last 30 years of rainfall data found that there was a probability of 30-78% across the sites of achieving these optimal conditions. The minimal condition for some recruitment detected in these studies was at least 7 days of moist soil, which had a high probability of 72-98%. These analyses suggest that in most years some recruitment would occur and that if possible farmers rest paddocks from spring through to late March if seasonal conditions permit to maximise the opportunities for recruitment. Further rests would then continue if seedlings had emerged.

9. The conditions for survival of young plants were not resolved in this study due to low frequency of survival. General observations though suggested competition may be the biggest factor during early stages of survival. Light grazing over 12-52 weeks of emergence is an option once seedlings become robust. The subsequent survival of young plants may

depend more on maintaining adequate soil moisture conditions and reducing competition through summer. Guidelines developed for managing sown pastures would be applicable to managing pastures through natural recruitment at this stage in our understanding of these ecosystems.