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Restoration treatments improve seedling establishment in a degraded Mediterranean- type *Eucalyptus* ecosystem

Katinka X. Ruthrof,[A,B] *Tegan Douglas,*[A] *Michael C. Calver,*[A] *Paul A. Barber,*[A] *Bernard Dell,*[A] *and Giles E.St.J. Hardy*[A]

[A] Western Australian State Centre of Excellence for Climate Change, Woodland and Forest Health, Murdoch University, South Street, Murdoch, WA 6150, Australia.

[B] Corresponding author. Email k.ruthrof@murdoch.edu.au

Abstract. Restoration of degraded Mediterranean-type ecosystems (MTE's) with long, hot and dry summers is challenging. To develop management guidelines we evaluated techniques that could improve seedling establishment in two degraded *Eucalyptus gomphocephala* DC. (tuart) woodlands, given weed and herbivore control. These techniques aimed to mimic favourable conditions for species that primarily recruit following disturbance events (e.g. fire). Trial 1 investigated the response of five-month-old seedlings and broadcast seed in plots that contained a created ashbed, were ripped, or were ripped and contained an ashbed. Trial 2 examined the response of five-month-old seedlings to treatments providing a nutrient or moisture source (slow-release fertiliser tablet, chelating agent, slow-release fertiliser tablet plus chelating agent, zeolite, hydrated hydrophilic co-polymers and dry hydrophilic co-polymers). Results indicated that created ashbeds enhances establishment for a range of species and reduces weed cover, with or without ripping. Broadcast seeding was not successful in returning species to site. Higher growth rates were recorded in seedlings treated with a nutrient source. This study has shown that it is possible to re-establish local plant species in degraded woodlands through a number of techniques that mimic

disturbance (e.g. fire). Strong early growth may be the vital start seedlings need in MTE's in the face of re-invading weed species, herbivory and a drying climate.

Introduction

Forest and woodland decline and degradation in Mediterranean-type ecosystems (MTE's), characterised by the death of extant plants, loss of a seedbank, and failure of the population to regenerate, are becoming increasingly severe in the Mediterranean Basin (de Dios *et al.* 2007), California (Chevone *et al.* 1988) and southern Australia (Marsh *et al.* 1995; Stone *et al.* 1995; Jurskis 2005; Scott *et al.* 2009). These declines are often caused by complex interactions including habitat loss and fragmentation, changes in land management techniques (e.g. fire management and forestry practices), changes in hydrology, pests and pathogens, weeds and climate change (Jurskis 2005; Close *et al.* 2009; Lindner *et al.* 2009; Ozkan *et al.* 2009). One management response is to refine management intervention guidelines for restoring woodland structure and function (Yates *et al.* 1997; Close *et al.* 2003; Vallejo *et al.* 2006), as a complement to research into diagnosis of the cause(s) and mitigation of decline. Refining restoration techniques is required to maintain ecological processes in declining systems to ensure that they do not pass a restoration threshold beyond which recovery is difficult or impossible (Hobbs *et al.* 1996; Hobbs *et al.* 2001).

Planting nursery-raised seedlings (or greenstock) is a favoured method of reintroducing propagules as an element of the restoration process because direct seeding has relatively low success rates (Clarke 2002; Close *et al.* 2003; Banerjee *et al.* 2006; Standish *et al.* 2008a). However, in the long, hot and dry summers of MTE's, seedlings with immature root systems often suffer water stress, stunted early growth or mortality (Kozlowski *et al.* 1975; Roche *et al.* 1998). Restoration techniques that maximise survival and growth in the early establishment phase are therefore vital in

MTE’s and are becoming particularly important given the need to undertake restoration within the context of a drying climate (see de Dios *et al.* 2007).

Site preparation prior to restoration activities (such as soil cultivation) is often recommended (Vallejo *et al.* 2006; Graham *et al.* 2009), but techniques based on the life history characteristics and early establishment requirements may also improve seedling establishment and restoration success. Plant species of MTE’s have morphological and ecological adaptations to post-fire regeneration through resprouting and fire-stimulated reseeding (Pausas *et al.* 1999; Rundel 1999), as seen for example, in studies of natural regeneration in southern Spain, (Ojeda *et al.* 1996), California (Moreno *et al.* 1992; York *et al.* 2009), and Australia (Yates *et al.* 1994b; Ruthrof *et al.* 2003). For instance, in temperate eucalypts, *en masse* germination and seedling establishment is contingent on large-scale disturbances such as fire, followed by timely rainfall, which facilitate seed fall and germination (Yates *et al.* 1994a; Ruthrof 2001; Ruthrof *et al.* 2002; Ruthrof *et al.* 2003). The effect of fire on natural recruitment is due mainly to the *ashbed effect,* and the fire that creates it, which increases the levels of available nitrogen and phosphorus (Loneragan *et al.* 1964; Humphreys *et al.* 1965; O'Dowd *et al.* 1984; Chambers *et al.* 1994; Romanya *et al.* 1994; Cummings *et al.* 2007), destroys or displaces pathogens and herbivores (Renbuss *et al.* 1973; Whelan *et al.* 1979), increases water infiltration and availability (Hatch 1960; Loneragan *et al.* 1964) and removes competition for light, nutrients and water from surrounding vegetation (Wellington *et al.* 1985; Bond *et al.* 1996). As a result, seedlings growing on ashbeds often have higher survival rates, greater height and higher biomass than seedlings growing elsewhere (Cremer 1962; Abbott *et al.* 1984; Burrows *et al.* 1990; Battaglia *et al.* 1993).

Accordingly, the success of woodland restoration in MTE’s could be increased by mimicking ecosystem processes such as disturbances (e.g. fire), or providing key resources available in a post-disturbance environment prior to the introduction of propagules through planting seedlings or seeding. For example, canopy removal (mimicking the removal of competition) increases survival of planted seedlings in *E. salmonophloia* woodlands in Western Australia (Yates *et al.* 2000a), burning increases survival and growth of planted *E. blakelyi* seedlings (Li *et al.* 2003), fertilisation (mimicking higher nutrient availability) increases early establishment of *Acacia salicina* in degraded sites in southeastern Spain (Oliet *et al.* 2005) and watering and the addition of composted biosolids (mimicking increased moisture and nutrient availability) results in higher survival rates and seedling performance in *Pinus pinaster* in Valencia (Estrela *et al.* 2009). A number of these treatments, such as canopy removal and burning, however, may not be appropriate in the restoration of degraded MTE woodlands or forests. The removal of adult plants or the reintroduction of fire may prove more destructive than beneficial, given the potential lack of a seed source. In these ecosystems, the creation of artificial ashbeds (to mimic a post-fire environment) using coarse woody debris (CWD) may be more appropriate. Created ashbeds could provide some of the resources that would naturally occur in a post-fire environment; however, these have not been trialled and published before within a restoration context for a range of species. Nevertheless, where the creation of artificial ashbeds is impractical or the use of fire prohibited, other site and plant treatments that increase the early establishment success of seedlings in restoration need to be found.

In this paper we apply this general principle for restoring degraded woodlands to the case of *Eucalyptus gomphocephala* (tuart), a declining woodland tree endemic to calcareous and alkaline soils on the Swan Coastal Plain of southwestern Australia (Brooker *et al.* 1990; Eldridge *et al.* 1994). The *E. gomphocephala* dominated woodlands are highly valued for biodiversity conservation and protecting ecosystem function, as well as providing important cultural, social and economic values. However, due to clearing for housing and agriculture and a massive decline in health in some areas, less than 30% of the original extent of these woodlands remains. Evidence from sources . Fox 1981) suggests that *E. gomphocephala* benefits from the effects of an ashbed. In this paper, we aimed to confirm the responses of *E. gomphocephala* to created ashbeds, test the responses of a range of common understorey species in this environment, and investigate effects of various treatments where the creation of ashbeds is not feasible. Therefore we aim to answer the following questions at two sites within the distribution of *E. gomphocephala,* the Ludlow Tuart Forest and Yalgorup National Park:

i) Is it possible to re-establish local plant species in the declining and degraded Mediterranean-type *E. gomphocephala* woodland ecosystem?; and

ii) Do soil and plant treatments that mimic some of the conditions available in a post-fire environment (e.g. nutrient and moisture sources) aid in early seedling establishment?

Given that there is considerable evidence to demonstrate that grazing and invasive species must be controlled for any restoration program to be successful (see Yates *et al.* 1997), this paper will focus on other factors that may be necessary to improve restoration techniques. We focused on inexpensive and simple-to-apply techniques applicable for broadscale use in restoration activities. The results will further improve restoration techniques for *E. gomphocephala,* as well as other degraded MTE woodlands and forests.

Materials and Methods

Two trials were undertaken to investigate improving early seedling establishment and growth in *Eucalyptus gomphocephala* woodlands. The first was in the Ludlow Tuart Forest, and considered the effects of created ashbeds and ripping techniques on the early establishment and growth of seedlings and broadcast seed. The second, located in the Yalgorup National Park area, where the creation of ashbeds was not permitted due to financial constraints and safety concerns, focused on the effects of soil treatments on the early establishment and growth of seedlings. The treatments mimicked some post-fire characteristics including increased availability of nutrients and moisture and were a slow release fertiliser tablet, a chelating agent, the slow release fertiliser tablet plus the chelating agent, zeolite, hydrated hydrophilic co-polymer crystals, and dry hydrophilic co-polymer crystals (Table 1).

Trial 1: Ludlow Tuart Forest

The Ludlow Tuart Forest (2049ha) is located 200 km south of Perth, Western Australia on the southern edge of the Swan Coastal Plain, parallel to the coastline (33°35'08.72"S 115°29'30.57"E). The average annual rainfall is 811.9 mm, 80% of which falls between May and September (BOM 2009a). The nearest weather station is Busselton Shire, 15 km SW of the site. The soils are classified as part of the Spearwood Dune System, consisting of variable depths of siliceous, brown and yellow leached sands (McArthur *et al.* 1974) derived from an underlying aeolianite of Tamala Limestone (McArthur *et al.* 1974; Gozzard *et al.* 1989; McArthur 1991).

The study site is representative of many of the *E. gomphocephala* woodlands within its distribution which were logged in the nineteenth and early twentieth century (Heberle 1997) and subject to grazing (mainly by cattle) since the early 1900's. Although the Ludlow Tuart Forest has many healthy *E. gomphocephala* adults, there is little natural recruitment and a lack of understorey diversity (DEC 2007).

The trial used a randomised complete block design, using blocks measuring 40 m x 10 m, each of which contained four plots of 10 m x 10 m. The blocks were replicated seven times across the Ludlow Tuart Forest site, which has an area of approximately 108 ha (DEC 2007). Given that the area was vulnerable to kangaroo grazing, the trial blocks were fenced. All blocks were sprayed with herbicide (1% Glyphosate), two weeks prior to planting, to control invasive weeds such as *Ehrharta longiflora*. The treatments were allocated randomly to the plots in each block. The treatments, and rationale for the use of each, were:

1) ripping: seedling establishment and growth is maximised when bulk density is decreased (Corns 1988; Yates *et al.* 2000b).

2) created ashbeds: seedlings have higher survival rates and grow taller on ashbeds due to: high N and P availability (Humphreys *et al.* 1965); a reduction in pathogens and herbivores (Renbuss *et al.* 1973); increased water availability (Hatch 1960); and reduced competition (Wellington *et al.* 1985).

3) ripping plus created ashbeds: see 1) and 2) above; and

4) control (no treatment).

Descriptions of treatments and method of application are outlined in Table 1. Creation of log piles for ashbeds and ripping plots was carried out in August 2006 using logs collected from within the area. Logs were of varying sizes, but generally from larger trees of over 20 cm in diameter. Log piles were burnt in May 2007 following the start of the winter rains.

The study species were: *Eucalyptus gomphocephala* (the dominant canopy species), *Acacia cochlearis* (Labill.) H.L.Wendl., *Kunzea ericifolia* (Sm.) Heynh., *Kunzea recurva* Schauer, and *Melaleuca incana* R.Br. (common associated understorey species). Seeds for the experiment were collected from as close to the site as possible, to ensure seeds were from the correct provenance. Both broadcast seeding (following pre-treatments if required) and planting was carried out, with broadcast seeding by hand taking place on the 14th June 2007 and the planting of five-month-old seedlings using Potiputki tree planters on the 24th June 2007. Species were mixed within each plot. Rates of broadcast seed and number of seedlings per plot are listed in Table 2.

Given that the first year is the most critical period for the establishment of seedlings following the long, dry and hot mediterranean summer (Savill *et al.* 1997; Benayas *et* *al.* 2002; Castro *et al.* 2004), monitoring was undertaken one year after planting following the end of the summer period. Survival of each species in every plot and the height (cm) of five randomly chosen plants per species were recorded. Percentage weed cover and number of recruited seedlings from seed were recorded in three 1 m^2 sub-plots per treatment in all blocks.

Trial 2: Yalgorup National Park

Yalgorup National Park (12 888ha) is located 100 km south of Perth, Western Australia and lies along the western edge of the Swan Coastal Plain, parallel to the coastline for approximately 60 km (115^{o}40'E, 32^{o}45'S). The average annual rainfall is 882.1 mm, 80% of which falls between May and September (BOM *et al.* 2009b). The nearest weather station is Mandurah Park, 25 km NE of the study site). The area lies on the Spearwood Dune System (Portlock *et al.* 1995) which consist of variable depths of siliceous, brown and yellow leached sands (McArthur *et al.* 1974) derived from an underlying aeolianite of Tamala Limestone (McArthur *et al.* 1974; Gozzard *et al.* 1989; McArthur 1991).

The study was conducted at three *E. gomphocephala* woodland sites within or near Yalgorup National Park: 1) a private property adjacent to the National Park (PP) 2) within Yalgorup National Park (YNP); and 3) a woodland north of the National Park, called Harry Perry Reserve (HP). The study sites are representative of many *E. gomphocephala* woodlands in the region and have been subject to various forms of degradation such as grazing, weed invasion and changed fire regimes (Archibald 2006). The three sites are highly degraded with a scattered canopy, a failure of natural recruitment, a loss of understorey diversity and cover, and extensive invasion by a wide range of non-native species.

The trial was made up of nine blocks, three at each of the three sites. Each block contained seven plots. Yalgorup National Park and the adjoining private property are particularly vulnerable to kangaroo grazing, so the trial blocks were fenced. All blocks were sprayed with herbicide (1% Glyphosate), two weeks prior to planting, to control invasive weeds including dune onion weed (*Trachyandra divaricata*) and annual veldt grass (*Ehrharta longifolia*). The treatments were allocated randomly to plots. The treatments and the constituents of each, application rates and method of application are outlined in Table 1. The rationale for the use of each treatment were:

1) A slow release fertiliser tablet was placed directly below the root ball at planting. A nutrient resource may mimic a post-fire nutrient release. Broadcast fertilisers were not used, as these would be readily used by invasive species;

2) A chelating agent, which, anecdotally, facilitates the uptake of nutrients to plants and enhance the effect of the fertiliser tablet;

3) The fertiliser tablet plus the chelating agent. This may mimic the post-fire nutrient release;

4) Zeolite is a highly porous mineral with a high water-holding capacity, which may provide seedlings with additional moisture;

5) Hydrated hydrophilic co-polymer crystals which are acrylic crystals with a high water-holding capacity, and may provide seedlings with additional moisture over the summer drought period;

6) Dry hydrophilic co-polymers crystals (see above). These dry crystals would expand with the winter rains and provide seedlings with additional moisture over the summer; and

7) Control (no treatment was added to the seedlings).

Given the high number of treatments tested, only a single species, *Eucalyptus gomphocephala,* was used in this trial. Twenty five, five-month-old *E. gomphocephala* seedlings, grown from provenance seed, were planted into the private property plots, and twenty seedlings were planted into each plot at the two other sites, totalling 1260 seedlings (Table 2). Plants were planted at 1 per square metre. Planting took place in early June 2007 using Potiputki tree planters. Survival and height (cm) were recorded for each seedling following the drought period, one year after planting. Given the lower number of seedlings in Trial 2, the additional measurement of health was carried out. Each seedling was given a rating from 1-5; 1 being dead, 5 being healthy (after Ruthrof 1997).

Statistical analyses

Trial 1: At the Ludlow site, the layout for analysing the survival and height of seedlings followed a randomised complete block design, with the three treatments on each species and the controls included in each of seven blocks. The dependent variable in the case of survival was the percentage of seedlings of each species surviving, while in the case of height it was the height of each of five randomly selected surviving seedlings for each treatment x species combination in each block. No *Acacia cochlearis* survived in the ripping treatment or the control in block 4, so the analysis of height was run with *A. cochlearis* excluded. Data were heteroscedastic and this could not be corrected by data transformation, so the significance value was set at 0.01 rather than 0.05 (Tabachnick *et al.* 2001).

The number of recruits of all species combined across the treatments was assessed with χ^2 goodness of fit, with the expected values calculated on the assumption that recruitment would be equal in all treatments. The percentage weed cover across the treatments was assessed using ANOVA.

Trial 2: There were three different sites at Yalgorup, with three replicates of each experimental treatment at each site. This corresponds to a two-way ANOVA design with factors of site and treatment and dependent variables of the percentage of seedlings surviving, mean height and mean health in each replicate. Each dependent variable was analysed separately, with the significance values set to 0.017 after

Bonferroni correction because of the multiple dependent variables. The variable health was not suited to parametric analysis because values were recorded on an ordinal scale, so health was analysed with a two-way Kruskal-Wallis non-parametric procedure (Sokal *et al.* 1995), pp. 446-447).

Results

Is it possible to re-establish local plant species in the declining and degraded Mediterranean-type E. gomphocephala woodland ecosystem?

Trial 1: Ludlow Tuart Forest

The overall survival rate for the planted seedlings after one year was 68 ± 4 %. There were significant differences between species ($F_{(4,72)} = 47.2$, $p < 0.001$). Specifically, *E. gomphocephala* and *Kunzea ericifolia* had the highest level of survival of all species used in the trial (84 ± 3 % and 81 ± 3 % respectively), followed by *Acacia cochlearis* (71 ± 5 %), *Kunzea recurva* (59 ± 4 %) and *Melaleuca incana* (44 ± 3 %).

Seedlings were also found to be recruiting from the broadcast seed, the existing canopy seed store, and from the soil seed bank (Table 3). Species that were noted in the area, but not within the 1 m x 1 m quadrats, were: *Thysanotus* spp*., Hardenbergia comptoniana, Jacksonia furcellata* and *Gompholobium tomentosum*.

Trial 2: Yalgorup National Park

Overall survival rates for the seedlings after one year was 65 ± 3 %. Survival was significantly different between the three locations ($F_{[2, 42]} = 92.7$, $p < 0.001$). The National Park site had 76 ± 4 % survival, the private property 85 ± 2 %, and Harry Perry 34 ± 4 %.

Do soil and plant treatments that mimic conditions available in a post-fire environment (nutrient and moisture sources) aid in early seedling establishment??

Trial 1: Ludlow Tuart Forest

Seedling survival differed significantly across the treatments ($F_{[3, 72]}$ = 14.2, p < 0.001). There was no difference in the survival of plants growing in ripped soils compared to the control plants. Plants of all species growing on the ashbed and ashbed+ripping treatments had higher survival rates than those on the ripping or control treatments (Figure 1). Although this seemed most marked in *E. gomphocephala* seedlings, there was no significant interaction between species and treatment ($F_{[12, 72]}$ = 1.4, p = 0.20).

Heights, excluding *A. cochlearis*, also differed significantly across the treatments ($F_{[3, 441]}$ = 44.06, p < 0.0001). The ashbed and ripping+ashbed treatments produced taller plants when considering the response of all species grouped together (Figure 1). This effect was evident across the study species (Table 4). Heights differed significantly between species ($F_{[3, 441]}$ = 194.32, p < 0.001), as expected given that the species were of different life forms. The interaction between species and treatments was not significant at the 0.01 level ($F_{[54, 441]}$ = 1.51, p = 0.011).

The number of seedlings that recruited from seed were similar across all treatment (Table 3, χ^2_3 = 1.04, n.s). The recruited seedlings were very small (<5cm) at the time of monitoring, regardless of treatment.

Thorough weed control was achieved. Weed cover averaged 5 ± 1 % across all blocks, but weed cover differed significantly across the treatment plots ($F_{[3, 56]}$ = 4.0, p < 0.0122). The ashbed (2 ± 0 %) and ashbed + ripping (3 ± 1 %) treatments had significantly lower (p < 0.05) weed percentage cover compared with the control plots (6 ± 1 %).

Trial 2: Yalgorup National Park

There was no significant difference between survival rates in the different treatments ($F_{[6,42]}$ = 1.8, p = 0.12) (Figure 2). However, the pattern in the data suggested the fertiliser alone and the fertiliser+ chelating agent treatments promoted the best survivorship at all sites while the zeolite treatment appeared to do less well than the controls. There was no significant interaction between site and treatment ($F_{[12,42]}$ = 0.6, p = 0.85). The dry hydrophilic co-polymer crystals had the tendency to push seedlings out of the ground when they hydrated following rainfall events. A number of these seedlings remained on the surface and suffered from desiccation.

There were significant differences between sites with regards to early growth, ($F_{[2,42]}$ = 92.7, p < 0.001). The private property had the tallest seedlings (66 ± 2.0 cm), followed by Harry Perry (38 ± 1 cm) and Yalgorup National Park (38 ± 1 cm). There were significant treatment responses ($F_{[6,\ 421]}$ = 5.3, p < 0.01). Seedlings treated with the fertiliser and the fertiliser plus the chelating agent grew taller (Figure 3). There was no significant interaction between site and treatment ($F_{[12,42]}$ = 1.2, p = 0.28).

Health differed significantly across the sites ($H_{(2)}$ = 40.0, p < 0.001). Plants at the private property were the healthiest. The effect of treatments on health was not significant ($H_{(6)}$ = 8.8, p > 0.05), nor was the treatment x Site interaction ($H_{(12)}$ = 3.7, p > 0.9).

Discussion

Is it possible to re-establish local plant species in the declining and degraded Mediterranean-type E. gomphocephala woodland ecosystem?

This study has shown that it is possible to reach early establishment stage for a range of common local plant species in degraded or declining *E. gomphocephala* woodlands. The overall survival rate of all study species in Trial 1 was moderate at 68 %. The major canopy species, *E. gomphocephala,* had a mean survival rate of 84 %. Results for *E. gomphocephala* from Trial 2 were slightly lower at 65 %. The early establishment survival rates in these trials are similar to those found in restoration trials using *E.*

gomphocephala in a comparable MTE in Western Australia, where seedlings had a first-year survival rate of 82 % (Ruthrof 2005). However, they are somewhat higher than in a degraded woodland in the more arid wheatbelt in Western Australia following one year (all percentages are approximate): *Eucalyptus salmonophloia* (30%), *Acacia hemiteles* (40 %) and *Melaleuca pauperiflora* (15 %)(Yates *et al.* 2000a). The survival rates following one year in other MTE's is similar, for example, after one year in control plots of *Pinus sylvestris* seedlings in south-east Spain a 33% survival rate was recorded (Castro *et al.* 2004). In southern Spain, seedlings of a range of tree species had varying survival rates after one year (all percentages are approximate): *Quercus ilex* (40 %), *Q. pyrenaica* (20 %), *Acer granatense* (15 %), *Sorbus aria* (30 %), *Pinus sylvestris* (0 %), *Q. suber* (20 %) and *Q. canariensis* (20%) (Maranon *et al.* 2004). Some of these results seem quite low, however, it is well established that the first year is the most challenging for seedling survival in the restoration of MTE's (Benayas *et al.* 2002; Castro *et al.* 2004).

These results demonstrate a number of key issues. Firstly, the moderate to high level of early establishment in this study, regardless of site or plant treatment, could be regarded as a success in the short term. Secondly, the establishment rates in this study provide an incentive to increase the scale of restoration efforts in degraded and declining MTE woodlands to prevent these systems from potentially degrading further to a point of not being able to be restored, even with high levels of management input. That is, before these types of sites cross restoration thresholds where basic restoration techniques are no longer useful (Hobbs *et al.* 1996; Hobbs *et al.* 2001).

The high levels of early seedling survival, growth and health found in this study is in stark contrast with the decline of adult *E. gomphocephala* plants in the Yalgorup National Park region (Archibald *et al.* 2005; Scott *et al.* 2009). This suggests that there is either a time lag in the effect of decline and the seedlings are yet to be affected, or there is some degree of seedling plasticity. That is, seedlings may be better able to adapt to sub-optimal conditions than the adults because they have been exposed at an early age (Kitajima *et al.* 2001). It also suggests that the decline in the adult trees could be caused by a sudden change in an environmental variable. This is supported by the work of Edwards (2004) who suggested that the decline in *E. gomphocephala* in the Yalgorup region may be associated with recent changes in groundwater quality. If this is the case and seedlings continue to thrive when adults decline, the early establishment success of the seedlings in this study may provide an opportunity to establish a new population of the canopy species, even though the existing population may become locally extinct in the long term. A longer term survival study will be required to further investigate this.

Although seedlings in this study had high early survival rates, the use of broadcast seeding was not as successful. This has been noted in a number of MTE woodlands such as in eucalypt woodlands in Australia (Standish *et al.* 2008b), woodland in southern Spain, where broadcast seeding of six tree species was only possible under wet conditions (Mendoza *et al.* 2009), and in woodlands in northeast Spain, where the revegetation success of *Pinus nigra* using seed was poor (Espelta *et al.* 2003). Low levels of success following broadcast seeding has also been noted in other species that recruit following fire, such as *Sequoiadendron giganteum* (York *et al.* 2009). However, other studies have demonstrated that broadcast seeding can be successful in woodland restoration (Boydak 2003). A number of factors affect the success of broadcast seeding including timing, temperature, moisture availability, light, seed predation, soil erosion, pathogens, seed harvesting, allelopathy and overstorey density (Yates *et al.* 1994a; Stoneman *et al.* 1995; Ruthrof *et al.* 2003). In our study, emergence from broadcast seed and natural recruitment (from both canopy seed store and soil seedbank) occurred, but seedlings were small. It is likely that a number of the limiting factors mentioned above played a role in this result. Methods of overcoming limitations to broadcast seeding for MTE woodland restoration will need further research.

Do soil and plant treatments that mimic conditions available in a post-fire environment (nutrient and moisture sources) aid in early seedling establishment?

This study has demonstrated that soil and plant treatments, such as artificially created ashbeds, can aid early seedling establishment. Although the positive effect of ashbeds on eucalypt seedlings is well-known within silviculture and within forest ecosystems (Cremer 1962; Clinnick *et al.* 1981; Fagg 1987; Burrows *et al.* 1990), at some sites used for old-field revegetation (Close *et al.* 2010) and amending burnt slash piles with native seeds can increase the cover of native forbs and grasses (Korb *et al.* 2004), the use of created ashbeds have not been tested within a restoration context for a range of species. This study has shown that firstly, ashbeds can be created for restoration purposes. Secondly, survival and growth rates are significantly higher in the ashbed treatment for a range of species and thirdly, ashbeds (that is, the fire that created the ashbeds) significantly reduced the percentage cover of invasive species. Following the outcomes of this study, created ashbeds are now being used in broadscale restoration of the Ludlow Tuart Forest. Further research is now being undertaken to try to achieve similar ecological restoration outcomes with lower amounts of coarse woody debris.

Given that coarse woody debris (CWD) may not always be available in declining or degraded woodlands (e.g. due to low availability, use for faunal habitat or fungi inoculum), the aim for restoration researchers should now be to a) use this resource more effectively, e.g. reduce the size from 10m x 10m but increase the abundance of ashbeds in an economic way and b) use novel and innovative site and plant treatments to achieve similar levels of survival and growth as recorded on ashbeds. With this in mind, Trial 2 (Yalgorup) assessed the responses of seedlings to the addition of nutrient and moisture sources where the creation of ashbeds was not permitted.

Despite the value of additional nutrients in enhancing early establishment, they can also favour introduced species that can out-compete seedlings for limited resources (Fensham *et al.* 1992). This is where slow-release fertiliser tablets, placed beneath the root ball of each seedling plant at the time of planting, could be beneficial. In this study, *E. gomphocephala* seedlings responded positively in terms of growth to slow-release fertiliser tablets, regardless of site. Thus, it seems that the addition of a nutrient source has the potential to assist the growth of seedlings in *E. gomphocephala* restoration at a broader scale, rather than being site-specific.

The positive response to fertiliser addition in this study has been noted in other studies in MTE's, such as increased establishment seen in *Pinus halepensis* and *Acacia salicina* in south east Spain (Oliet *et al.* 2009) and (Oliet *et al.* 2005) respectively, and increased performance (height, width and condition) in a range of plant species in *Banksia* woodland restoration in Western Australia (Rokich *et al.* 2007). This pattern has also been noted in other degraded ecosystems (Ruthrof 1997; Close *et al.* 2003; Clemente *et al.* 2004). However, the addition of a nutrient source has not been tested before for increasing the success of restoration for a range of plant species in degraded *E. gomphocephala* woodlands. Particularly in MTE sites with low nutrient soils (Oliet *et al.* 2005; Vallejo *et al.* 2006), and where post-fire regeneration is characteristic (Pausas *et al.* 1999; Rundel 1999), a significant positive growth response to a nutrient source may be the vital early start needed as practitioners aim to create resilient communities in the face of a drying climate, competition from reinvading weed species, and herbivory.

Seedling treatments that were not as successful in this trial with regards to early establishment and growth, in the manner in which they were applied, included the hydrophilic co-polymer and zeolite. These results are similar to those documented by others. In a study of reforestation of a semiarid MTE, (Barbera *et al.* 2005) found the addition of a hydrophilic acrylic copolymer reduced *Pinus halepensis* growth during the first months of reforestation. Ayan *et al.* (2006), who investigated the influence of different growing media (peat, fine pumice, course pumice, river sand, perlite and river sand, all with and without the addition of zeolite) on *Pinus sylvestris,* noted that height, root collar diameter, root dry weight, stem dry weight and total dry weight were lower in the zeolite added media. It seems that the addition of a moisture source in close proximity to the seedling root ball may not be as efficient as the addition of nutrients in increasing early establishment success.

Additional work is now required to further improve the success of early establishment of a range of species in *E. gomphocephala*, and other MTE forests and woodlands. There is a need to determine the mechanism(s) by which ashbeds facilitate the success of early establishment and growth of a range of plant species in a restoration context, so that the factor or factors responsible can be targeted and mimicked in sites where ashbed creation is not feasible.

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Table 1. Description of treatments applied in the restoration trials within the Ludlow Tuart Forest and Yalgorup National Park

No.	Treatment	Application notes
Trial 1: Ludlow Tuart Forest		
1	Ripping	Ripped to 30cm, single-tyne, 30cm spacing. Due to the potential to damage extant canopy plants, deep ripping was not used.
2	Ashbed	Large woody debris (~20cm diameter logs) was placed into plots to 1m height and burnt in May 2007
3	Ripping plus Ashbed	Following ripping, large woody debris placed into plots and treated as above
4	Control	No treatment
Trial 2: Yalgorup National Park		
1	Fertiliser tablet Typhoon (Sunpalm Australia, Wangara, Western Australia) (10gm):	Constituents: Total N (ammonium and urea 20.0%), Total P (phosphate water soluble, citrate soluble and citrate insoluble 4.40%), K (sulphate 8.2%), Ca (phosphate 4.0%), S (sulphate and phosphate 6.0%), Mg (oxide 0.2%), Cu (sulphate 0.03%), Zn (oxide 0.50%), Fe (sulphate 0.16%), Mn (sulphate 0.16%), Mo (molybdite 0.01%) and B (tetraborate 0.01%). One 10gm tablet was placed beneath the root ball of each seedling at planting.
2	Chelating agent	A starch-based liquid containing sugar cane, seaweed extracts, aloe vera, phytoproteins, trace elements. One cup of diluted (10%) product was applied to each seedling at planting.
3	Fertiliser tablet plus chelating agent	A combination of the two treatments described above.
4	Zeolite	A naturally occurring mineral, a hydrated alumino-silicate. It has a micro-porous structure, a large surface area for trapping and exchanging nutrients, and is marginally alkaline. Anecdotal evidence suggests it can absorb 55% of its weight in water, increases root and shoot growth, yield, and reduces leaching. One third of a cup of zeolite was placed beneath the

		root ball of each seedling at planting.
5	Hydrated hydrophilic co-polymer crystals	Acrylic hydrophilic co-polymer that soaks up 400 times its weight. The crystals were hydrated in water at a rate of 1tsp/500ml. A half cup of hydrated crystals was placed below the root ball of each seedling at planting.
6	Dry hydrophilic co-polymer crystals	1tsp of dry crystals was placed below the root ball of each seedling at planting.
7	Control	No treatment

Table 2. Species planted, number of seedlings planted, amount of broadcast seed (equiv. gm/ha) and germination requirements for species per plot for Trial 1: Ludlow Tuart Forest and Trial 2: Yalgorup National Park.

Note: PP=private property, YNP= Yalgorup National Park, HPR= Harry Perry Reserve.

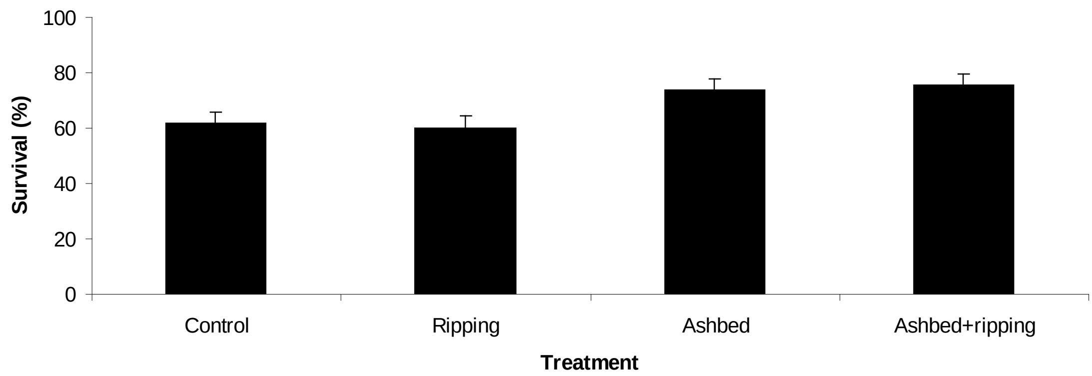
Species planted	Number of seedlings planted per plot	Amount of broadcast seed (equiv. g/ha)	Germination requirement (pre-treatment undertaken prior to broadcast seeding)
Trial 1: Ludlow Tuart Forest			
Acacia cochlearis	14	95	Boiling
Eucalyptus gomphocephala	20	60	No pre-treatment required
Kunzea ericifolia	20	40	No pre-treatment required
Kunzea recurva	20	40	No pre-treatment required
Melaleuca incana	20	20	No pre-treatment required
Trial 2: Yalgorup National Park			
Eucalyptus gomphocephala	25 PP, 20 YNP, 20 HPR	N/A	No pre-treatment required

Table 3. Number of recruits from broadcast seeding, canopy seed store, or soil seedbank in Trial 1: Ludlow Tuart Forest one year following seeding.

The number of recruits are totals from 84 1m x 1m quadrats.

Species/treatment	Number of recruits after 1yr	Source
Acacia cochlearis	4	Broadcast seed or soil seedbank
Agonis flexuosa	7	Canopy seed store
Corymbia calophylla	1	Canopy seed store
Eucalyptus gomphocephala	3	Broadcast seed and canopy seed store
Kennedia prostrata	9	Soil seed bank
Kunzea ericifolia	20	Broadcast seed
Kunzea recurva	7	Broadcast seed
Melaleuca incana	3	Broadcast seed
Gompholobium tomentosum	0	
Trachymene coerulea	0	
Unidentified	12	
Treatment		
Ashbed	18	Various
Ripping	19	Various
Ashbed+Ripping	15	Various
Control	14	Various

a)



b)

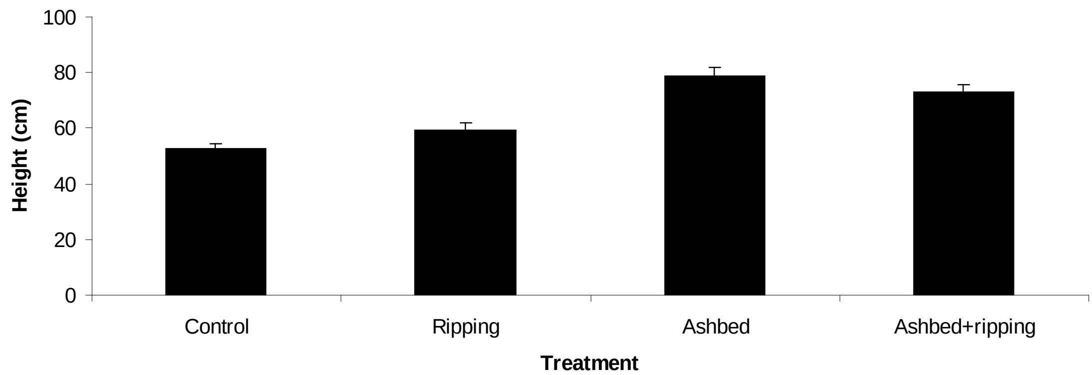


Fig. 1. a) Mean percentage survival (%) and b) mean height (cm) of seedlings one year after planting in four different treatments (Control, Ripping, Ashbed and Ashbed+ripping) in Trial 1: Ludlow Tuart Forest. Values are means (± standard errors) of 658 seedlings for survival, and 175 for height. Note that both the percentage survival and heights of seedlings are higher in the Ashbed and Ashbed+ripping treatments.

Table 4. Height (cm) of each species within each treatment following one year in Trial 1: Ludlow Tuart Forest.

Values are means (standard errors) of 35 surviving seedlings per species. Figures in bold are significantly different from the control using post-hoc Tukeys honest significant difference test for unequal sample sizes. Note that for most species the Ashbed and the Ashbed+ripping resulted in taller seedlings.

Species	Control	Ripping	Ashbed	Ashbed+ripping
Eucalyptus gomphocephala	66.7 (3.8)	79.8 (7.9)	**117.0 (7.7)**	**96.8 (6.2)**
Kunzea ericifolia	76.7 (5.2)	83.6 (6.8)	**104.3 (5.9)**	**104.5 (5.0)**
Kunzea recurva	52.2 (3.0)	60.9 (4.3)	**70.2 (4.4)**	**67.2 (3.2)**
Melaleuca incana	25.8 (2.6)	34.6 (2.9)	33.4 (2.6)	30.9 (2.2)

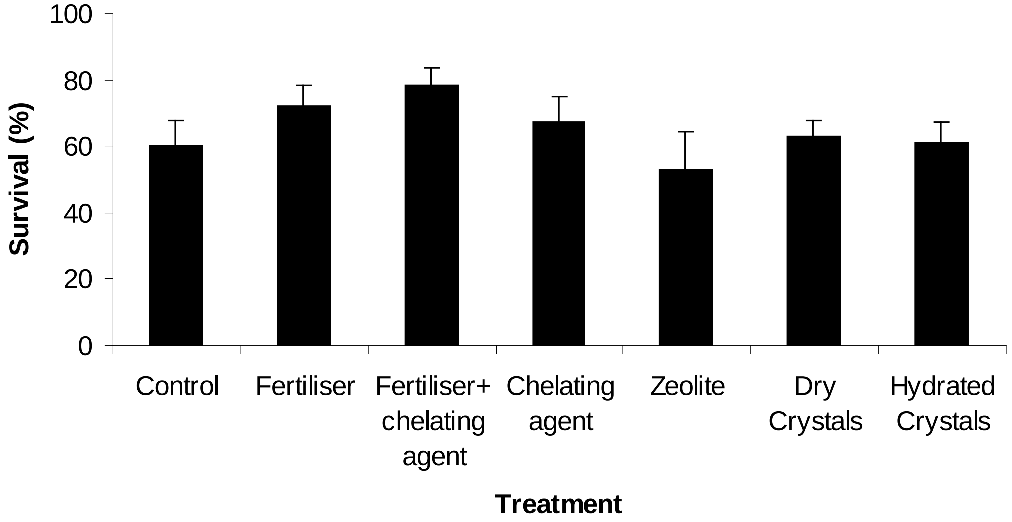


Fig. 2. Mean percent survival (%) of *E. gomphocephala* seedlings following one year of growth in Trial 2: Yalgorup National Park. Values are means (± standard errors) of 195 seedlings.

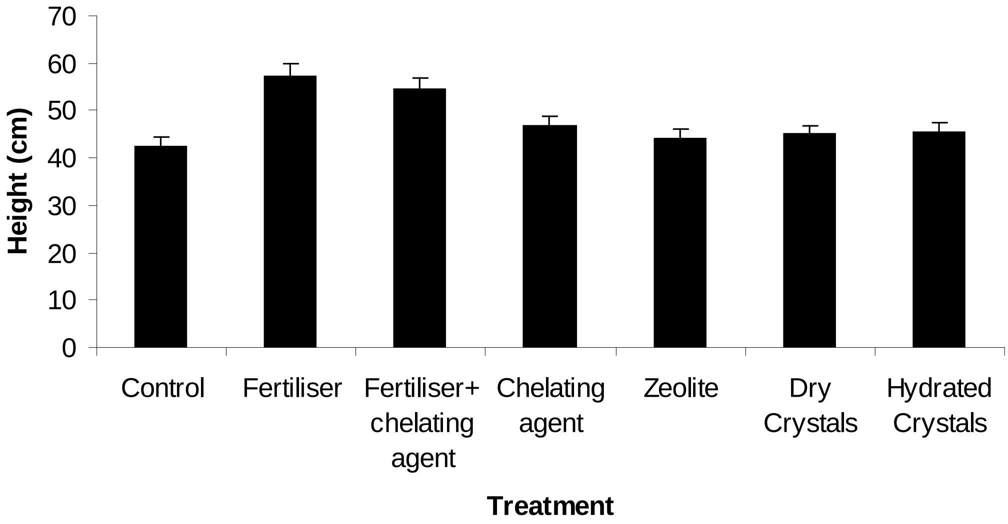


Fig. 3. Mean height (cm) of surviving *E. gomphocephala* seedlings following one year of growth in Trial 2: Yalgorup National Park. Values are means (± standard errors) of 195 seedlings. Note that the fertiliser and fertiliser + chelating agent treatments resulted in taller seedlings.