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Linking restoration outcomes with mechanism: the role of site preparation, fertilisation and revegetation timing relative to soil density and water content

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Abstract Global land use and ongoing climate change highlight the importance of ecological restoration as an emerging discipline and underscore the need for successful revegetation techniques. To link mechanistic drivers of seedling establishment with techniques to increase revegetation success, we undertook field-based experiments in degraded peri-urban woodlands in Mediterranean southwestern Australia using two iconic tree species. Over the course of an entire growing season, our objectives were to: 1) characterise soil moisture profiles in relation to site preparation techniques (ripping and created ashbeds) and 2) determine whether early seedling establishment can be increased through site preparation techniques (ripping and ashbeds), plant treatments (various fertilisers and biochar) and early planting during the wet season. Ripping significantly reduced soil compaction and was associated with a significant soil moisture stratification; moisture penetrated to greater depths in soils that were ripped or treated with ashbeds. Particular site preparation techniques (ripping) and early planting significantly increased early establishment, health and growth of tree seedlings. Fertilisation effects varied by species with generally neutral effects on seedlings. Finally, seedlings planted in ripped soils had significantly longer, deeper root systems accessing portions of the soil profile with higher summer moisture. Techniques such as ripping, even in deep sandy soils, reduce soil compaction and alter moisture availability within the soil profile, promoting deeper root growth and thus increasing revegetation success in these degraded Mediterranean ecosystems. Linkage of revegetation outcomes with plant response and physical soil properties associated with particular treatments provides critical knowledge for both restoration scientists and land managers.

Keywords Moisture profile, seedling establishment, root growth, restoration

Introduction

Conservation and passive management of degraded ecosystems is widely recognised as an insufficient strategy to ensure autogenic, spontaneous recolonisation and recovery of native assemblages and ecosystem function (Hobbs 2007; Jackson and Hobbs 2009). Active management efforts to restore ecosystems is necessary, for example, the active transport of plants and animals to places they no longer exist (Lawler and Olden 2011). Despite mounting species losses and a pressing need for active species return, technical expertise to restore ecosystem composition, structure and function lags with many more failures than successes (Lockwood and Pimm 1999; Benayas et al. 2009), leading some to label ecological restoration as one of the most important emerging disciplines in environmental science (Montoya et al. 2012; Shackelford et al. 2013)

Revegetation and restoration efforts in Mediterranean-type climate ecosystems (MCEs) are a particularly crucial, given their global importance as biodiversity hotspots and disproportionate level of land conversion and grazing pressure they experience (Le Houerou 2000; Klausmeyer and Shaw 2009), as well as weed invasion, altered fire regimes, changes in hydrology, resulting in further loss of species and alteration of ecosystem function (Yates and Hobbs 1997). Within this context of mounting challenges, the scope for restoration activities that are required are profound (Hobbs et al. 2011).

Given the broad array of degrading factors present, the need to understand mechanistic effects of both basic drivers of Mediterranean systems (e.g. soil water availability during summer) and development of techniques to enhance vegetation establishment and persistence are paramount (Standish et al. 2012). Although there is clearly some uncertainty regarding the long term survival and growth of seedlings, the first year in particular seems the most critical in seedling establishment in MCEs (Gomez-Aparicio et al. 2004; Padilla and Pugnaire 2007) as the timing of opening rains and water availability during summer drought determines the growing season length, root production and hence survival and persistence (Martinez et al. 1998). The importance of the first year following revegetation will become ever more important in an increasingly unpredictable Mediterranean climate as the effects of climate change become more apparent (Bacilieri et al. 1993; Klausmeyer and Shaw 2009).

Several practical site preparation techniques have shown to increase the establishment success of planted seedlings in MCEs, including ripping (mechanically disturbing the top 5-100cm of the soil to increase roughness and negate compaction and soil erosion) (Turner et al. 2006; Koch and Samsa 2007), and ashbed creation (combustion of coarse woody debris piles) which increases water infiltration and nutrient availability (Hatch 1960; Loneragan and Loneragan 1964). Plant treatments that have been shown to increase seedling establishment include the addition of nutrients (Martinez et al. 1998; Ruthrof et al. 2010), though treatment effects may vary across species, site and other treatments such as watering (Standish et al. 2012). New and novel treatments are also being explored in a revegetation context, such as biochar. Biochar is produced by thermal decomposition of organic material in an atmosphere limited in oxygen and at low temperatures to prevent complete combustion (Lehmann and Joseph 2008). It has an extremely high surface area and cation exchange capacity to support microbiota that can increase plant nutrient availability (Winsley 2007) and can improve soil structure and water retention (Chan and Xu 2009). Biochar is used as a site preparation technique in combination with composts, manures and other amendments (Beesley et al. 2011). However, although biochars' properties may be potentially attractive, their ecological efficacy must be determined (Beesley et al. 2011).

Although ripping, nutrient amendments and related techniques and treatments have been shown to favour early seedling establishment in MCEs (Yates et al. 2000; Ruthrof et al. 2010; Ruthrof et al. 2012), there seems to be little mechanistic understanding of why these techniques work in terms of moisture profile differences and their effects on seedling establishment over time. Increased understanding of these mechanisms and potential outcomes for plant survival and growth could increase success of a broad range of restoration activities across scales, including in degraded forests, old mine sites and abandoned agricultural lands.

To link revegetation interventions and outcomes with mechanistic understanding of treatment effects, we implemented field experiments at two sites using two iconic tree species in the southwest of Western Australia to aid in maintaining them in the landscape. To this end, we asked the following questions:

- In the first year of seedling establishment, what impacts do site preparation techniques such as ripping and ashbeds have on soil moisture profiles, soil compaction and plant rooting depth?
- How do these site preparation techniques, timing of planting, and plant-scale fertilisation influence seedling survival, growth and health following the first summer?

We aimed to answer these questions, focusing on the dominant canopy species, *Eucalyptus gomphocephala* DC., and a its associated mid-storey tree species, *Agonis flexuosa* (Willd.) Sweet, in two woodlands on the sandy Swan Coastal Plain of Western Australia: Ludlow Tuart Forest and Yalgorup National Park. These sites represent some of the most degraded woodlands on the Swan Coastal Plain, underscoring the need to develop revegetation techniques to achieve desired restoration outcomes.

Methods

Study sites

Ludlow Tuart Forest (Ludlow) (2, 049 ha) is located 200 km south of Perth, Western Australia (33°35'08.72"S 115°29'30.57"E). The region has a Mediterranean-type climate, with an average annual rainfall of 817mm (Busselton, WA, 15km SW of site), 80% falling between May and September. For the period June 2009-May 2010, Busselton experienced lower than average July, August, December, January March and May rainfall, and an annual total of 728mm (BOM 2012). Soils are classified as the Spearwood Dune System, consisting of variable depths of siliceous, brown and yellow leached sands (McArthur and Bettenay 1974). The study site is representative of many of the *E. gomphocephala* (Tuart) woodlands in the region with a history of logging in the 19th and 20th centuries (Heberle 1997) and cattle grazing since the early 1900s. Extensive invasions of exotic plants have occurred, including Arum Lily (*Zantedeschia aethiopica*) and Black Berry Nightshade (*Solanum nigrum*). Although Ludlow has many healthy adult *E. gomphocephala* (average canopy cover of the study area: 27.2 ± 1.2%) there is poor natural recruitment and a loss of understorey plant diversity (DEC 2007).

Yalgorup National Park (Yalgorup) (12, 888 ha) is located 100 km south of Perth, Western Australia (115^{o}40’E, 32^{o}45’S). The area experiences 875 mm of rainfall annually (Mandurah, WA, 25km NE of site), 80 % of which falls between May and September. Over the period June 2009-May 2010, Yalgorup experienced lower than average October, December, January and February and the total annual rainfall was 630 mm (BOM 2012). Like Ludlow, Yalgorup lies on the Spearwood Dune System. The study site is highly degraded, subjected to extensive grazing and weed invasion (e.g. dune onion weed, *Trachyandra divaricata*) with a scattered deteriorating overstorey canopy (average canopy cover of the study area: 2.3 ± 0.9%), a lack of natural tree recruitment, and a loss of understorey diversity and cover. Both sites are affected by kangaroo grazing and invasive plant species, so the trials were fenced and sprayed using 1% Glyphosate in late May before planting.

Experimental design

A randomised block design was used, including 20 m x 10 m blocks with each containing five 4m x 10m treatment plots. Blocks were replicated three times at each site. Plant treatments were randomly allocated to plots and were: 10 g fertiliser tablet, 10 g fertiliser tablet + biochar, 20 g fertiliser tablet, 2 x 20 g fertiliser tables (= 40 g) and a control where no treatment was added (Table 1).

The three blocks were replicated within two types of site preparation techniques, ripping to approximately 40 cm of depth using a tractor (furrow spacing of 1m), and control (no ripping), totalling six blocks at each site. At Ludlow only, three ashbed plots were created as an additional site treatment, outside the six blocks (this technique was not permitted in Yalgorup). Ashbed plots were created by piling woody debris into piles, approximately 4 m x 10 m, and burnt two weeks prior to planting. No fertilisers were added to the ashbed treatment. Treatments and their chemical constituents, application rates and method of application are outlined in Table 1.

Trials included both *Eucalyptus gomphocephala* (the dominant canopy species) and *Agonis flexuosa* (a dominant mid-storey species). Twenty plants of each species were planted into each plot or ashbed at 1/m^2. Six-month-old, healthy seedlings (mean heights: *E. gomphocephala* = 37 ± 0.8 cm, *A. flexuosa* = 22 ± 0.8 cm) using Pottiputki™ tree planters in early June 2009 to coincide with the onset of winter rains. Plant treatments were included with seedlings at the time of planting.

In MCEs, virtually all planting activity takes place during the winter months (June, July and August). However, there is considerable debate over timing of seedling planting. While many practitioners wait for the soil profile to be sufficiently damp (mid-winter), others argue for early planting to aid in root growth and establishment (Palacios et al. 2009). To test the effect of timing of planting on survival, growth and health, we planted an additional three plots of 20 *E. gomphocephala* seedlings (from the same batch of plants but kept in pots for a longer period of time) later in the wet season (late July) at Yalgorup. One plot was placed at the end of each unripped block (Supplementary Figure 1).

Monitoring of soil moisture

Soil moisture content was measured using a PR2/6 multi-depth soil moisture probe; a sealed polycarbonate rod consisting of a series of capacitance sensors used to determine volumetric soil moisture content (% vol) at 10, 20, 30, 40, 60 and 100 cm depths (PR2/6 Delta-T Devices Ltd., Cambridge, UK) (Delta-TDevices 2004; Garcia et al. 2009). The PR2/6 has a measurement sphere of 2-3 cm. Access tubes for soil moisture measurements (27 mm diameter carbon fibre tubes) were installed within each of the three site preparation treatment blocks, including control plots (no treatment), ripped and ashbed treatments at Ludlow as well as the ripped and control blocks at Yalgorup to test the soil moisture profile response to site preparation. Three access tubes were randomly placed in ripped and control plots, away from seedlings. In addition, access tubes were also placed into the three non-ripped, late planting plots at Yalgorup (design similar to (Suleiman 2007)). Thus, there were nine access tubes at each site, totalling 18 tubes. Moisture was measured monthly from November 2009 to July 2010.

Soil penetrability

Soil penetrability, as a measure of soil compaction, was measured using a bulk density meter (Eijkelkamp Agrisearch equipment 06.01 hand penetrometer). At each site, measurements were taken at depths of 5, 10, 15, 20, 25 and 30 cm and replicated twice within each block (control, ripping and ashbed for Ludlow; and control and ripping for Yalgorup).

Seedling responses

Given that the first year is the most critical period for seedling establishment (Savill et al. 1997; Benayas 1998), monitoring was undertaken one year after planting. To assess treatment efficacy, each plant was assessed for survival (live or dead), height (to the nearest cm), and health (categorical assessment). Seedling health was rated from 1-5; 1 being dead, 5 being healthy, taking into account general vigour, crown density, colour and amount of herbivory (Ruthrof 1997, 2001; Ruthrof et al. 2010).

In December 2009, at the beginning of the summer period, 22 *E. gomphocephala* and *A. flexuosa* seedlings were randomly selected for excavation in ripped and non-ripped blocks at Yalgorup only in order to determine root depth. All roots were carefully extracted in the field and roots measured for length.

Statistical analysis

We assessed survival, height and health of both tree species by site using linear mixed effect models using a binomial distribution for survival and normal distribution for height and health. Effect sizes and their 95% confidence intervals are presented where lack of overlap was interpreted as evidence of a statistical difference between groups. Sites were analysed separately given their distinct management histories and differences in canopy cover. Seedling data from ripped plots at Ludlow were excluded due to accidental herbicide application during the study, thus seedling responses to ripping were not assessed at this site. Treatment effects on soil conditions (moisture and compaction) are presented relative to block-scale (ashbed, ripping) treatments with means and 95% confidence intervals.

To estimate effect of fertiliser type, ripping and timing of planting on seedlings we employed a mixed effect model, allowing for a random effect of block (n = 6 per site) and plot (n = 30 per site). Analyses were conducted in R 2.13 (R 2011) using the lme4 package (Bates and Maechler 2011). In all cases, we assessed evidence for interaction effects of block-scale treatments (ripping, ashbed) and plot-scale treatments (fertiliser) by comparing an additive model and a full model containing an interaction term. Following suggestions by Zuur et al (2009), we assessed evidence on the basis of likelihood ratios using models fit with restricted likelihoods and examined model residuals for lack of homogeneity and poor fits. We found no evidence for interactions among treatments and thus present results of additive models.

Results

Site preparation effects on soil properties and rooting depth

Soil bulk density: across sites, ripping treatments significantly reduced soil bulk density (as measured by resistance, MPa) of soil in the top 30cm (Ludlow, Table 2, Fig 1a) and 25cm (Yalgorup, Table 2, Fig 1b) of the soil profile. Site effects were evident with soils at Ludlow possessing much greater bulk densities than those at Yalgorup (2 versus 8 MPa at 30cm depth, Fig 1a, b). Effects of ashbeds at Ludlow were similar to that of ripping at the soil surface though with retained effect (of lower bulk densities) at greater depths. There was also a much lower heterogeneity in the ashbed bulk densities, as reflected by substantially narrower 95% confidence intervals (Fig. 1a).

Soil moisture profiles: site preparation treatment effects on soil moisture were evident, though differing in magnitude, at both sites (Table 2, Fig. 2). Overall soil moisture ranged from 0-

10.2% at Yalgorup and 0-11.9% at Ludlow. At both sites, low readings were recorded in November to February, and higher readings in June and July). At Yalgorup, the zone of effective ripping (25-30 cm) was substantiated by lower early summertime soil moisture and a more thorough wetting of the profile with onset of early winter rains relative to non-ripped controls (Fig 2). Ripping effects at Ludlow were similar to Yalgorup (Table 2, Fig 2). The ashbed treatment at Ludlow produced a larger magnitude of response (Table 2, Fig 2) with extremely dry profile (at times, 0%) at shallow (< 40 cm) depths in summer followed by relatively low soil moisture in winter in the upper profile. This suggests that ashbeds produce a greater effect of treatment compared with the ripping treatment (Fig 2).

Rooting depth: rooting depth was only measured at ripped and non-ripped plots at Yalgorup due to errant herbicide application at Ludlow (see Methods). Mean rooting depth of both *E. gomphocephala* (30 vs 58 cm) and *A. flexuosa* (35 vs 65 cm) was significantly deeper in ripped plots versus the non-ripped controls with non-overlapping 95% confidence intervals (Fig 3).

Effects on plant survival, height and health

Ashbed treatment at Ludlow had no significant effect on survival, height and health of *E. gomphocephala* seedlings (Figure 4) but had significant negative effects on *A. flexuosa* health and survival (Figure 4). In contrast, ripping at Yalgorup produced categorically strongly significant positive effects on both *E. gomphocephala* and *A. flexuosa* across height, survival, and health (Figure 5).

No evidence for interactions between site preparation (ashbed, ripping) and plant-scale fertilisation treatments were found; all top models were additive in their structure. At Ludlow, fertilisers were generally homogeneous in their effects with all four fertilisers displaying no effects on survival and health of *E. gomphocephala* (Figure 4). Height of *E. gomphocephala* was also largely unaffected by fertilisation though all effect estimates were positive with one, the 20 g treatment (Manutec 1X, Table 1), displaying a significant positive effect (Figure 4). The response of *A. flexuosa* at Ludlow generally mirrored that of *E. gomphocephala* with a pattern of no effect and a positive effect of the 20 g fertiliser on height but also with the same fertiliser having a significant negative effect on survival, underscoring a potential trade-off between growth and survival in *A. flexuosa* (Figure 4).

At Yalgorup, fertiliser effects on *E. gomphocephala* were again homogenous between fertilisers but broadly positive (most 95% confidence intervals not overlapping zero) with regard to survival, height and health and again with the 20 g Manutec 1X treatment producing the largest effect (Figure 5). The response of *A. flexuosa* was distinct from that of *E. gomphocephala*, showing generally neutral or negative effects of fertilisation, specifically, a negative survival and health response to Manutec 2X. However, the 10 g Typhoon fertiliser did show a significant positive effect on height with no effect on survival and health whereas all other fertilisers were all neutral or negative. Doubling of fertiliser to 40 g (Manutec 2X) did not lead to a significant increase in response in either species and in the case of *A. flexuosa* at Yalgorup decreased survival and health.

Timing of planting: effects of timing of planting (early versus late winter) was pronounced and produced the largest effects in the study, with late-planted *E. gomphocephala* showing significantly reduced survival, height and health relative to early planted seedlings (Figure 5, Supplementary Table 1).

Discussion

In this study low soil densities were associated with increased water infiltration, deeper rooting and increased early survival, growth and health in both tree species. Furthermore, planting earlier in the wet winter season was critical for revegetation success for the study species examined. Fertilisation produced broadly neutral (and sometimes negative) effects and did not interact with site preparation treatments (ripping or ashbeds). Previous work has demonstrated increased revegetation success with regard to added nutrients (Oliet et al. 2009; Ruthrof et al. 2010) but by linking treatment and mechanism we have presented evidence that promotion of deeper root growth and altered soil moisture profiles, particularly over the summer drought period, is the responsible mechanism for improved growth and survival.

Ashbed and ripping treatments in this study significantly lowered soil densities and led to lower soil moisture in the upper profile. This is consistent with previous work on ashbeds (Hatch 1960) and ripping (Hamza and Anderson 2008). In this study we found clear, unilaterally positive effects of ripping but neutral to negative effects of ashbeds on seedling survival, height, and health. Ripping is a commonly used tool in agriculture and revegetation to reduce soil compaction, particularly in clay-dominated soils (Yates et al. 2000; Sinnett et al. 2008). Previous research has demonstrated that ripping increases seedling survival and vigour in MCEs, including in reforestation activities in Spain (Barbera et al. 2005; Palacios et al. 2009), and in post-mining rehabilitation in Australia (Rokich et al. 2001), and degraded MCEs containing extant vegetation (Yates et al. 2000). However, this study represents the first to examine the effects of ripping, in deep sandy soils with extant vegetation.

In our study, ripping significantly reduced bulk density to a depth of 25-30 cm, increased water infiltration (and formed a stratified soil moisture profile), and was associated with deeper root architecture, higher survival and growth in both tree species at Yalgorup. It seems that in non-compacted, deep sandy soils, reduced bulk density and increased water infiltration can lead to increased seedling establishment, similar to clay-dominated substrates. In water-limited environments, planted seedlings increase root elongation rates in response to lower moisture availability (Padilla et al. 2007). As a consequence of rapid elongation, roots are situated at a sufficient depth where moisture is available during drought. Padilla and Pugnaire (2007) in Portugal found a strong positive relationship between survival and maximum rooting depth, as well as between soil moisture and survival. Clearly, planted seedling survival in MCEs is dependent on rapid root development during spring and early summer which is critical for keeping pace with the drying moisture zone and access to deeper layers of soils where moisture content is more constant (Barbera et al. 2005).

Fertilisation treatments had mixed effects on survival, growth and health with variation across species and sites. There were certainly differential species responses, which is not surprising, given that the two study species, although serotinous co-dominants, have slightly different life history characteristics. Recruitment niches are quite different; *E. gomphocephala* is a post-fire, canopy gap regenerator (Ruthrof et al. 2003), whereas *A. flexuosa* regenerates in interfire periods and in a post-fire environment. Thus, responses to nutrients are expected to be diverse. Previous work has shown an addition of nutrients increases planted seedling establishment success in degraded eucalypt woodlands in Western Australia (Ruthrof et al. 2010) and in reforestation of *Pinus halepensis* in south-eastern Spain (Oliet et al. 2009). However, nutrient addition interactions with water availability are complex and may interact with site history to produce uncertain outcomes (Standish et al. 2012), underscoring the importance of sequential revegetation trials and site-specific and species-specific information.

A further plant treatment tested in this study was biochar, which, in the method that it was produced and applied, did not significantly increase early seedling establishment, growth or health compared with the effect of the fertiliser that it was applied with. This could be due to: insufficient biochar to adequately supply seedlings, or the characteristics of biochar. There is little information related to the effects of biochar on trees, apart from applications to ailing trees, and particularly little information regarding biochar use in dry or temperate climates (Blackwell et al. 2009). Further work is required with regards to the development of biochar as a plant treatment, examining a broader range of concentrations and composition.

In this study, planting *E. gomphocephala* at the beginning of the Mediterranean winter period significantly increased all three measures (survival, growth and health) of early establishment success. These results have been reported from other MCEs across a range of species. In a study of *Quercus ilex* in Spain, Palacios (2009) noted that after two years of growth, seedlings planted on an early date showed the best survival rates (61%) compared with the same quality plants and soil preparation treatments on a mid-season planting date (40%). Higher survival rates from initiation early in the wet season has also been recorded for broadcast seeding in Western

Australia (Turner et al. 2006) and for natural recruitment in South Africa and California (Bond et al. 1984; Potts et al. 2010). Particularly in a MCE, weather affects soil temperature and moisture, and, consequently, the planting or intervention date could be a key factor affecting establishment. Seedlings require sufficient time and resources to develop drought-surviving root systems prior to summer (Potts et al. 2010). Thus, together with site preparation and plant treatments, it seems a careful selection of planting or intervention date (in the example of fire planning) plays an important role in the success of regeneration or revegetation.

Effects of all treatments varied by site in this study. Site preparation treatments (ripping) likely varied due to initial differences in compaction and soil bulk density (see Fig. 1); for example, Ludlow retained higher penetration resistance after ripping. Such differences may have contributed to differences in soil water relations, observed survival, growth and health between sites. Differences in fertilisation effects may have stemmed from herbicide overspray problems in some plots at Ludlow leading to increased variance in control plots and reduced power to detect effects. Site context is critical; ecological and management legacies often exert large influences on system resilience and capacity for revegetation (Standish et al. 2012). However, the scope of this work encompasses degraded Mediterranean woodlands in sandy soils and revegetation efforts focused at establishing planted seedlings of canopy dominants.

Conclusions

In this study, application of site preparation techniques (ripping, ashbeds) significantly reduced soil density and increased soil water infiltration. In these same soils, plant rooting depth of two iconic tree species was significantly deeper and survival, height and health were greater. Additionally, planting earlier in the wet season also significantly increased survival, height and health. Taken together, these outcomes link mechanism with revegetation practice – soil conditions and timing of planting are key considerations for revegetation while fertilisation is context dependent. Revegetation of MCEs is a rapidly growing field with an urgent need for detailed information and mechanistic understanding. Plant-scale fertilisation treatments were site and species specific, suggesting caution and placing a greater importance on site preparation techniques like ripping and ashbed creation. Site preparation techniques can alter moisture availability within the soil profile and, together with strategic plant treatments, can increase revegetation success in degraded MCEs.

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

No.	Treatment	Application notes
1	Control	No treatment applied
2	Fertiliser tablet (10gm). Typhoon (Sunpalm Australia, Wangara, Western Australia)	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 tablet was placed beneath the root ball of each seedling at planting.
3	Fertiliser tablet (10gm). Typhoon. (Sunpalm Australia, Wangara, Western Australia) + biochar	Constituents: as above + biochar. Biochar is produced by thermal decomposition of organic material in an atmosphere limited in oxygen and at relatively low temperatures to prevent complete combustion (Lehmann and Joseph 2008). For this trial, biochar was created by using coarsely chipped mixed *Eucalyptus* species stem and branch wood and two very simple conversion technologies: a portable batch kiln made from waste metal containers, and a dug pit covered with a removable metal cover sealed using soil. One 10gm Typhoon fertiliser tablet and ¼ cup (~ 20gm) of biochar was placed beneath the root ball of each seedling at planting. The addition of a compost or fertiliser is suggested (Beesley et al. 2011).
4	Fertiliser tablet (20gm) Manutec (Cavan SA 5094,	Constituents: Nitrogen (Urea Formaldehyde 20%), Total N (20%), P (citrate soluble 5%), Total P (5%), K (Sulphate 5%), Total P (5%), S (Sulphates 2.35%), Ca (Carbonate 1.9%), Mg (Magnesium

	Australia)	Oxide 0.414%), Mn (Manganese Oxide 0.07%), Mn (Manganese Sulphate 0.008%), Fe (Iron Oxide 0.048%), Fe (Iron Sulphate 0.220%), Cu (Copper Oxide 0.008%), Cu (Copper Sulphate 0.008%), B (Boric Oxide 0.004%), Mo (Sodium Molybdate 0.0005%). One tablet was placed beneath the root ball of each seedling at planting
5	Fertiliser tablets (2x 20gm): Manutec (Cavan, South Australia)	Constituents: as above. Two tablets were placed beneath the root ball of each seedling at planting.

Table 2. Mean effects (S.E.) of the site preparation techniques of ripping and ashbed on soil compaction and soil moisture in restoration trials in Ludlow Tuart Forest and Yalgorup National Park, Western Australia

		Soil Compaction MPa (Effect Size (SE))	t-statistic (P-Value)	Soil Moisture (% moisture) Effect Size (SE)	Test Statistic (P-Value)
Ludlow	Ripping	-1.8 (0.2)	7.7 (<0.0001)	1.4 (0.3)	4.8 (<0.0001)
	Ashbed	-2.7 (0.2)	14.4 (<0.0001)	1.4 (0.3)	4.5 (<0.0001)
	Depth	0.1 (0.01)	13.6 (<0.0001)	0.02 (0.004)	4.2 (<0.0001)
Yalgorup	Ripping	-0.5 (0.1)	7.9 (<0.0001)	-0.9 (0.2)	3.8 (<0.001)
	Depth	0.04 (0.003)	11.8 (<0.0001)	0.04 (0.004)	10.4 (<0.0001)

Notes: Overall model for soil compaction, $F_{3,216}$=109.6 (Ludlow) and $F_{2,69}$=101.7 (Yalgorup).

FIGURE LEGENDS

Fig. 1 Soil penetrability (MPa, mean + 95% confidence intervals) in control, ripped, and ashbed treatments at (a) Ludlow Tuart Forest (b) Yalgorup National Park, Western Australia.

Fig. 2 Soil moisture profiles for each measured treatment (ripped, non-ripped and ashbed at Ludlow Tuart Forest and ripped, non-ripped at Yalgorup National Park, Western Australia). N= three per treatment per site.

Fig.3 Mean (95% confidence interval) rooting depth (cm) of 11 randomly chosen *Agonis flexuosa* and *Eucalyptus gomphocephala* seedlings in non-ripped and ripped treatments at Yalgorup National Park, Western Australia.

Fig. 4 Effect (95% confidence intervals) of site preparation techniques (ripping, ashbed) and four fertilisation treatments on mean survival (%), height (cm) and health score (1-5) of two dominant tree species, *Eucalyptus gomphocephala* and *Agonis flexuosa*, relative to control seedlings in Ludlow Tuart Forest. Note: Char = biochar.

Fig. 5 Effect (95% confidence intervals) of site preparation treatment (ripping) and four fertiliser treatments on mean survival (%), height (cm) and health score (1-5) of two dominant tree species *Eucalyptus gomphocephala* and *Agonis flexuosa* relative to control seedlings in Yalgorup National Park. Note: Char = biochar

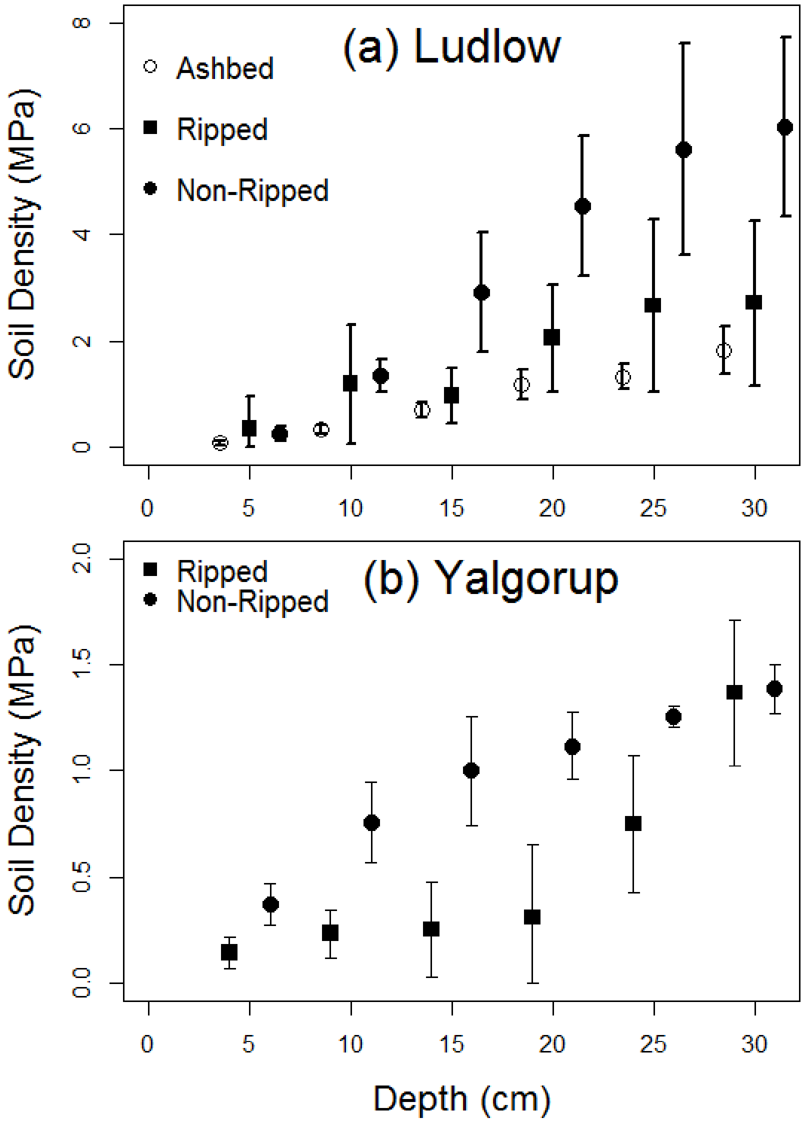
(a) Ludlow
○ Ashbed
■ Ripped
● Non-Ripped
Soil Density (MPa)
0
2
4
6
8
0
5
10
15
20
25
30
(b) Yalgorup
■ Ripped
● Non-Ripped
Soil Density (MPa)
0.0
0.5
1.0
1.5
2.0
0
5
10
15
20
25
30
Depth (cm)

Fig. 1

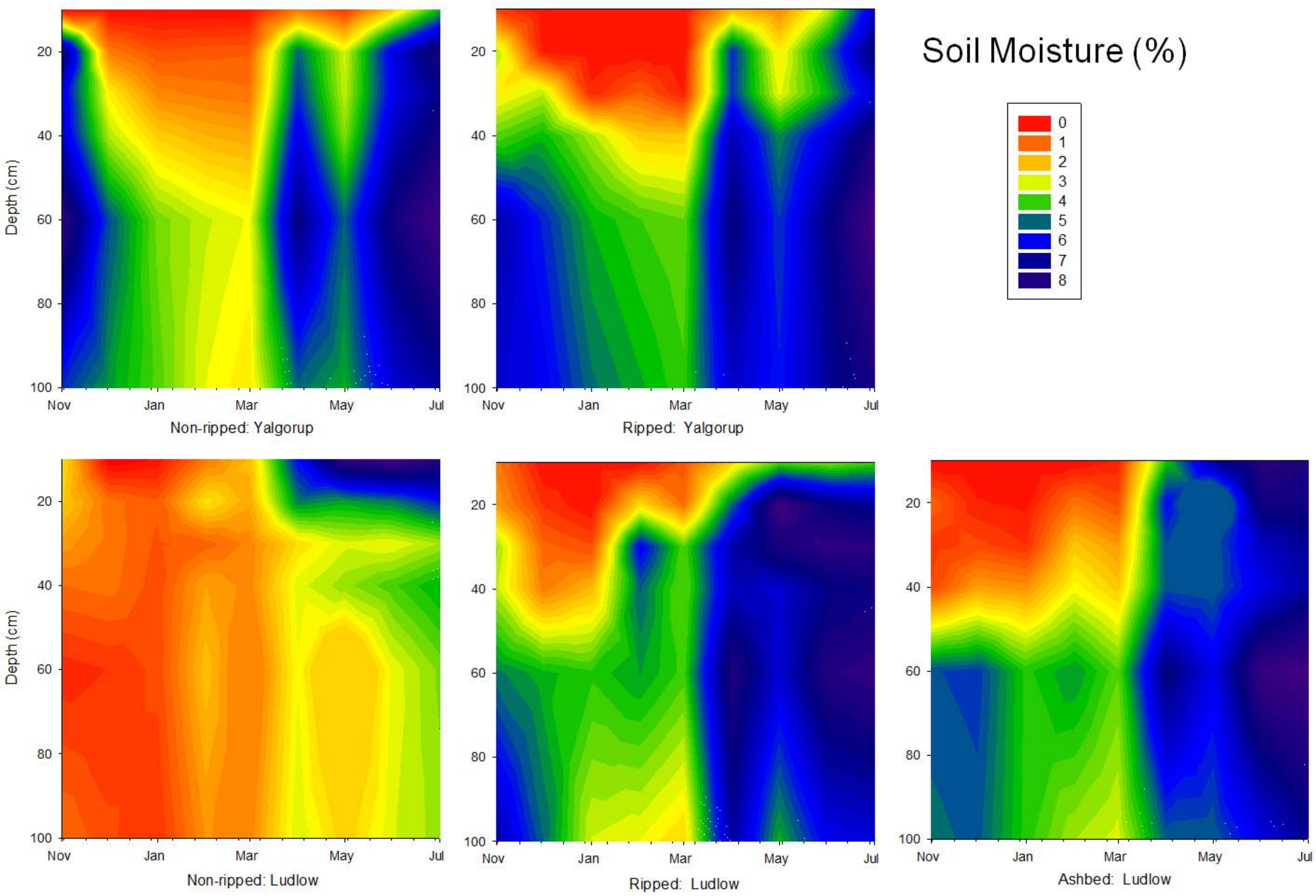
Soil Moisture (%)
🟥 0
🟧 1
🟨 2
3
🟩 4
5
🟦 6
7
8
Depth (cm)
20
40
60
80
100
Nov
Jan
Mar
May
Jul
Non-ripped: Yalgorup
Ripped: Yalgorup
Non-ripped: Ludlow
Ripped: Ludlow
Ashbed: Ludlow

Fig. 2

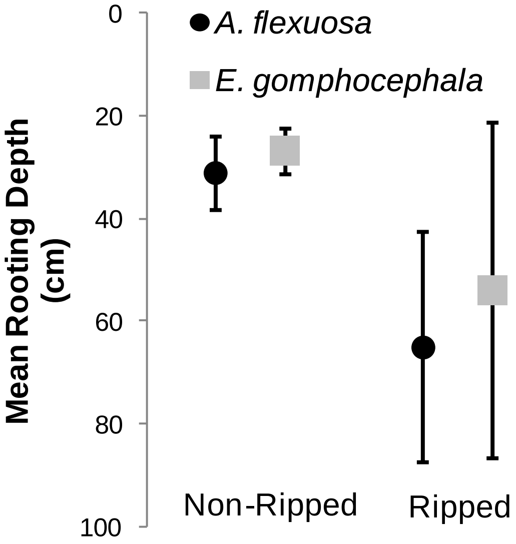
A. flexuosa
E. gomphocephala
Mean Rooting Depth (cm)
0
20
40
60
80
100
Non-Ripped
Ripped

Fig. 3

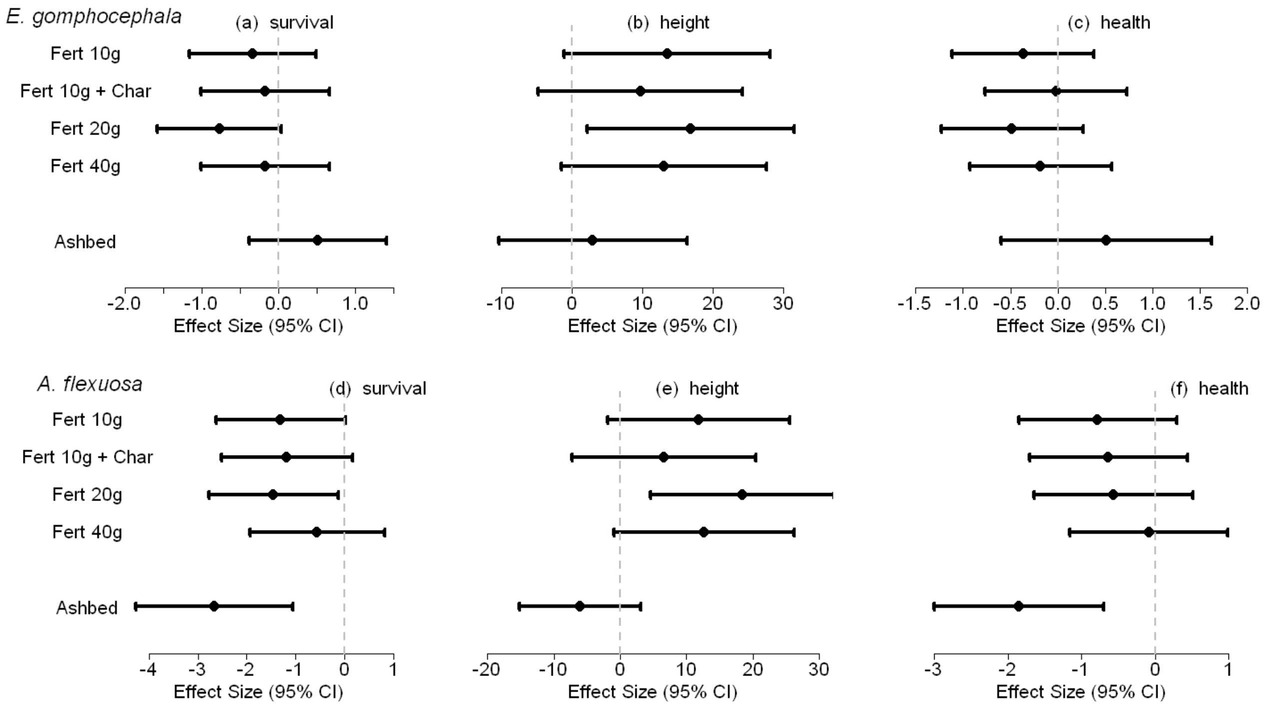
E. gomphocephala
(a) survival
(b) height
(c) health
Fert 10g
Fert 10g + Char
Fert 20g
Fert 40g
Ashbed
-2.0 -1.0 0.0 1.0
Effect Size (95% CI)
-10 0 10 20 30
Effect Size (95% CI)
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0
Effect Size (95% CI)
A. flexuosa
(d) survival
(e) height
(f) health
Fert 10g
Fert 10g + Char
Fert 20g
Fert 40g
Ashbed
-4 -3 -2 -1 0 1
Effect Size (95% CI)
-20 -10 0 10 20 30
Effect Size (95% CI)
-3 -2 -1 0 1
Effect Size (95% CI)

Fig. 4

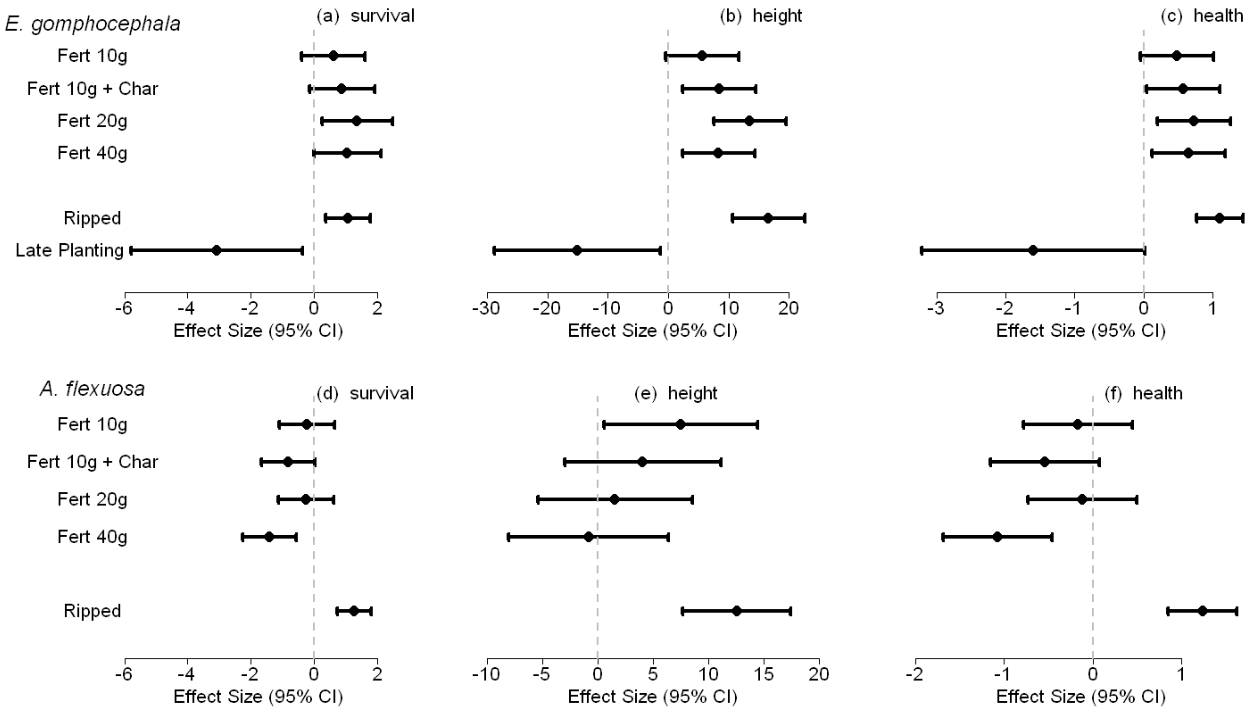
E. gomphocephala
(a) survival
(b) height
(c) health
Fert 10g
Fert 10g + Char
Fert 20g
Fert 40g
Ripped
Late Planting
-6
-4
-2
0
2
-30
-20
-10
0
10
20
-3
-2
-1
0
1
Effect Size (95% CI)
A. flexuosa
(d) survival
(e) height
(f) health
Fert 10g
Fert 10g + Char
Fert 20g
Fert 40g
Ripped
-6
-4
-2
0
2
-10
-5
0
5
10
15
20
-2
-1
0
1
Effect Size (95% CI)

Fig. 5

Supplementary Table 1. Mean (standard deviation) of mean survival (%), height (cm), and health scores (1-5) for seedlings of the two dominant tree species *Eucalyptus gomphocephala* and *Agonis flexuosa* monitored after one year following site preparation and fertilisation treatments at Ludlow Tuart Forest and Yalgorup National Park, Western Australia.

				Eucalyptus gomphocephala			*Agonis flexuosa*		
LUDLOW	Site Preparation Treatment	Plot Treatment	N plots	Mean survival (%)	Mean height (cm)	Mean health (1-5)	Mean survival (%)	Mean height (cm)	Mean health (1-5)
	Non ripped	Control	3	75 (10)	65.6 (12.8)	3.2 (1.5)	86.7 (15.3)	56.4 (17.1)	4 (1.4)
		Biochar+Typhoon	3	71.7 (10.4)	75.6 (21.1)	3.2 (1.5)	68.3 (30.1)	64.9 (20.8)	3.3 (1.8)
		Manutec x1	3	58.3 (2.9)	82.1 (18.9)	2.7 (1.5)	65 (13.2)	75.7 (24.9)	3.4 (1.9)
		Manutec x2	3	71.7 (12.6)	95.3 (119.1)	3 (1.5)	80 (18)	70.5 (25.6)	3.9 (1.5)
		Typhoon	3	68.3 (23.1)	79.2 (15)	2.8 (1.5)	70 (8.7)	67.7 (23.3)	3.2 (1.7)
	Non ripped Total		15	69 (12.8)	79.3 (56.7)	3 (1.5)	74 (17.7)	66.5 (23.1)	3.6 (1.7)
	Ashbed	Ashbed	3	83.3 (5.8)	68.4 (22.8)	3.7 (1.4)	38.3 (20.8)	50.3 (21.7)	2.1 (1.6)
YALGORUP									
	Non ripped	Control	3	73.3 (20.2)	57.3 (11.2)	3 (1.4)	70 (15)	27.6 (8.4)	3.3 (1.7)
		Biochar+Typhoon	3	81.7 (17.6)	62.7 (13.2)	3.4 (1.4)	48.3 (27.5)	38.4 (8.2)	2.6 (1.8)
		Manutec x1	3	86.7 (10.4)	71.2 (14.7)	3.7 (1.3)	48.3 (18.9)	33.2 (7)	2.7 (1.8)
		Manutec x2	3	86.7 (12.6)	63.8 (15.4)	3.7 (1.3)	31.7 (16.1)	33.4 (12.6)	2 (1.6)
		Typhoon	3	73.3 (7.6)	63.4 (14.5)	3.2 (1.5)	73.3 (18.9)	35.6 (10.6)	3.3 (1.8)
		Late planting	3	21.7 (25.7)	45.1 (11.7)	1.5 (1)			
	Non ripped Total†		15	80.3 (13.7)	63.9 (14.5)	3.4 (1.4)	54.3 (23.1)	33.4 (10)	2.8 (1.8)
	Ripped	Control	3	80 (13.2)	72.7 (15.8)	3.9 (1.5)	85 (5)	46.2 (13.6)	4.3 (1.4)
		Biochar+Typhoon	3	93.3 (2.9)	83.3 (16)	4.6 (1)	75 (8.7)	44.4 (11.5)	3.9 (1.7)
		Manutec x1	3	96.7 (2.9)	85.2 (13)	4.7 (0.8)	93.3 (7.6)	43.9 (10.9)	4.7 (1)
		Manutec x2	3	91.7 (14.4)	82.8 (12.4)	4.5 (1.1)	66.7 (7.6)	41 (13.4)	3.4 (1.8)
		Typhoon	3	95 (5)	77.6 (13)	4.7 (0.9)	75 (10)	52 (14.1)	4 (1.7)
	Ripped Total		15	91.3 (9.9)	80.5 (14.7)	4.5 (1.2)	79 (11.7)	45.5 (13.1)	4 (1.6)

†Does not include late planting so that numbers are directly comparable to non-ripped treatment at Ludlow Tuart Forest.

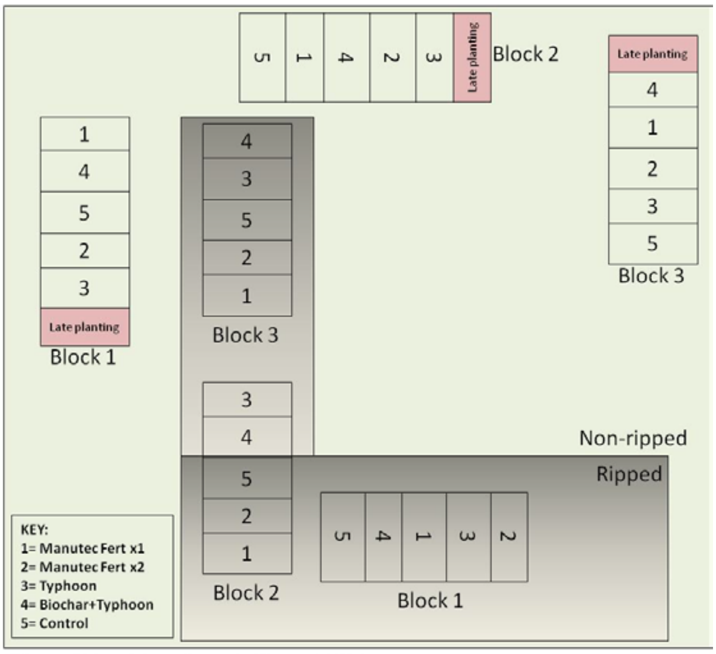

Figure S1 a. Experimental Layout: Yalgorup

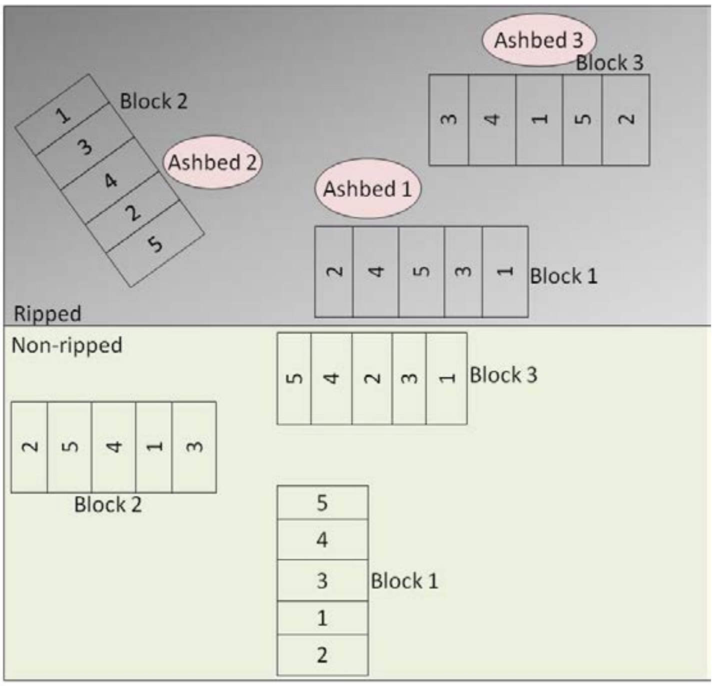

Figure S1 b. Experimental Layout: Ludlow