RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

SER SOCIETY FOR ECOLOGICAL RESTORATION

RE-AL THEMATIC SERIES

RESEARCH ARTICLE



Are planting site conditions more important than soil amendments when direct seeding in the semiarid Mallee in regional Victoria, Australia?

Joseph Stapleton[1,2], Shane R. Turner[3], David Warne[4], Singarayer Florentine[1,5], Jo-ann Larkins[1]

Direct seeding is a potentially valuable method for restoration in arid areas due to its low cost and labor input but suffers from the drawback of reduced survival rates, which may lead to planting failure. As such, the addition of soil amendments may be one way to increase planting success rates. This study investigated whether the addition of three types of soil amendments (fertilizers, hydrogels, and microbial inoculants) would be able to increase the emergence and survival times of direct seeding works in the semiarid Mallee region of north-west Victoria, Australia. Seed from four native species were mechanically directly seeded into three sites across the Mallee region, along with different combinations of soil amendments. Emergence and survival time were recorded for 1 year, and the soil properties at each planting location were analyzed. The results showed that only the two larger-seeded species (*Acacia ligulata* and *Callitris gracilis*) were able to emerge, while the two smaller-seeded species (*Eucalyptus calycogona* and *Melaleuca lanceolata*) showed no emergence. Soil amendments had no effect on either seedling emergence or survival time. Instead, seeding location had a significant outcome for both seedling emergence and survival. It was found that locations that showed the highest emergence did not necessarily show the highest survival. Low soil nutrient sandplains contained the highest seedling emergence counts. The longest surviving seedlings were in locations with slightly higher nitrogen levels for *A. ligulata* seedlings, while *C. gracilis* survived longest in highly sandy soil under a slightly cooler, wetter climate.

Key words: direct seeding, Mallee, restoration, seedling emergence, seedling survival, soil, soil amendments

Implications for Practice

- Fertilizers, hydrogels, and commercial microbial inoculants will likely provide no benefit to direct seeding restoration plantings in the Mallee region and should not be used in this environment.
- Site effects, such as soil properties, will have a large impact on direct seeding work, and direct seeding sites should be chosen based on the known preferences of the sown species.
- For *Acacia ligulata* and *Callitris gracilis*, direct seeding work should focus on sandy soil, such as sand dunes, as that will provide the best balance between emergence and survival rate.

Introduction

Direct seeding, where seeds are sown mechanically into a planting area, is a potentially valuable method for revegetation works that can restore large areas at a significantly reduced cost and labor intensity when compared to traditional hand-planted seedlings (Pérez et al. 2019). However, it is observed that this method comes with reduced chances of seedling survival (Palma & Laurance 2015; Pérez et al. 2019) due to their vulnerability when young to environmental conditions such as drought, weed competition, and predation (de Souza Gomes Guarino & Scariot 2014; Passaretti et al. 2020). As the seeds germinate and emerge in field conditions, the success rate of direct seeding will often depend greatly on environmental factors at

Author contributions: JS conceived and developed the first draft; all authors (JS, SRT, DW, SF, JL) made equal contributions to the material covered and to the discussion of all topics in subsequent drafts.

[1]Future Regions Research Centre, Institute of Innovation, Science and Sustainability, Federation University Australia, Mount Helen, Ballarat, Victoria 3350, Australia
[2]Address correspondence to J. Stapleton, email joseph.staple@gmail.com
[3]School of Molecular and Life Sciences, Curtin University, Bentley, Perth, Western Australia 6102, Australia
[4]Greening Australia, Level 3, 349 Collins Street, Melbourne, Victoria 3000, Australia
[5]Applied Chemistry and Environmental Science School of Science, STEM College, RMIT University, 124 La Trobe Street, Melbourne, Victoria 3000, Australia

© 2025 The Author(s). Restoration Ecology *published by Wiley Periodicals LLC on behalf of Society for Ecological Restoration.*
This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
doi: 10.1111/rec.70087
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.70087/suppinfo

project sites, such as timely rainfall (Figueiredo et al. 2021) and soil properties (Sampaio et al. 2019). Direct seeding may also favor seeds with particular traits, such as large seed size (Souza & Engel 2018) rather than smaller sized seeded species, and hence species selection will likely have a large impact on results. Some previous studies have considered that the significant reduction in cost and labor would potentially offset the decreased survival rates and higher variability (Pérez et al. 2019). However, other studies argue that the lower cost does not offset the disadvantages of decreased survival rates and that this method should only be used as a supplement to other planting methods with higher success rates, such as hand-planting (Ceccon et al. 2016).

One environment that may significantly benefit from the use of direct seeding is degraded arid lands (Stapleton et al. 2024b). The arid ecosystems of the world cover a large percentage (around 41%) of the terrestrial environment (Safriel et al. 2005) meaning that restoration works in this habitat need to take place on a large scale. Compounding these issues is that restoration works are often subject to low and short-term funding (Ewing et al. 2013) and increasing costs (Copeland et al. 2018), putting further strain on the finances of these projects. The above problems highlight the need for cost-effective techniques that can be applied on a large scale, such as direct seeding.

However, direct seeding in the arid zone may come with increased risk of revegetation failure. Arid ecosystems experience harsh environmental conditions, most notably water-scarce conditions with high variability (Huang et al. 2019), which can lead to reduced effectiveness of direct seeding work (Figueiredo et al. 2021).

A potential method for reducing seed mortality and increasing germination may be the use of soil amendments, which refers to a range of materials added to the soil to improve its physical and chemical properties. Some examples include hydrogels, fertilizers, and soil microbe inoculants. As is the case with direct seeding, each of these materials also has positives and negatives associated with their use. For example, hydrogels are relatively cheap (Negoita et al. 2021) and help store moisture in the soil (Wei et al. 2016) which is particularly useful in dry climates. However, these materials may prove to be ineffective under extremely dry conditions (Commander et al. 2013), which may impact their usage in arid areas. Fertilizers can increase initial growth rates, which can provide survival benefits in the field by increasing nutrient reserves and simulating the ability to grow roots (Oliet et al. 2009). However, fertilizers can have a negative effect on drought tolerance by increasing plants' aboveground growth over root growth, resulting in increased water loss through transpiration (Trubat et al. 2011). Fertilizer can also lead to an increase in weed growth, which may compete with planted seedlings (Silva et al. 2015). Microbial inoculants are a type of amendment that aims to add beneficial microbes into the soil. These microbes can improve the drought tolerance of plants by increasing emergence and survival rates (Azizi et al. 2022). However, commercial sources of microbial inoculants, which are the types that are most available to practitioners, introduce non-native soil microbes into the soil that may not be compatible with the species used in restoration (Moreira-Grez et al. 2019).

The objective of this study was to determine whether direct seeding in arid environments can be improved through the addition of soil amendments (hydrogels, fertilizers, and microbial inoculants) in terms of emergence numbers and survival through the first year. The first year of a seedling's life, particularly the first summer, is often an important bottleneck for seedling survival (Hallett et al. 2014) making it a critical time period to carry out investigations. In addition to soil amendments, another objective was to observe how environmental effects, namely soil properties and site rainfall, affect the success of seedling establishment.

Methods

Study Sites

The study took place in the Mallee region of north-west Victoria. This area is characterized by a semiarid climate with rainfall ranging between 250 and 450 mm per year. The landscape is composed mostly of gently undulating sandplains and sand dune fields. The native vegetation is dominated by the characteristic low-growing, multi-stemmed Mallee eucalypts with other tree and shrub species including species of *Melaleuca*, *Callitris*, and *Acacia* (White 2006). Much of the native vegetation was cleared post-European settlement for pasture and cropping, with around 72% of the original vegetation having been removed (White 2006).

Three sites were chosen for the project located in areas where *Greening Australia* was currently performing revegetation work (Fig. 1). Site 1 (35°30′43.34″S, 142°18′11.03″E) was located on the "Wathe" property, which is public land that had previously been used for cropping. Native vegetation bordered the site though the planting area had been cleared and was mostly composed of weedy forb and grass species. Site 2 (34°49′2.69″S, 142°23′1.34″E) was located on the "Cramenton" property, which is private land that had also been used for cropping, although this activity had stopped at least 30 years before this investigation. Like Site 1, native vegetation bordered the site but had been mostly cleared from the planting area with current vegetation made up of forbs, grasses, and a scattering of sticky Hop bush (*Dodonaea viscosa*). Site 3 (36°32′0.45″S, 141°13′39.99″E) was located on the "Salvanna" property, which is also located on private land, with the area being less intensively cleared compared to the previous two sites and hence had more native vegetation present at the planting sites.

Plot Establishment and Setup

The soil amendments used in the treatments were obtained from commercially available sources as most revegetation managers would have easy access to them. *Osmocote Exact Mini 5-6M* was the fertilizer product chosen as it is already used in Mallee restoration works. This came in the form of small slow-release granules, and the nutrient mix of the product was 15% nitrogen (nitrate and ammonia), 9% phosphorus pentoxide, 11% potassium oxide, 2% magnesium oxide, and 0.65% trace elements (boron, copper, iron, magnesium, molybdenum, and zinc). The hydrogel product used was *EarthCare Water Crystals* which

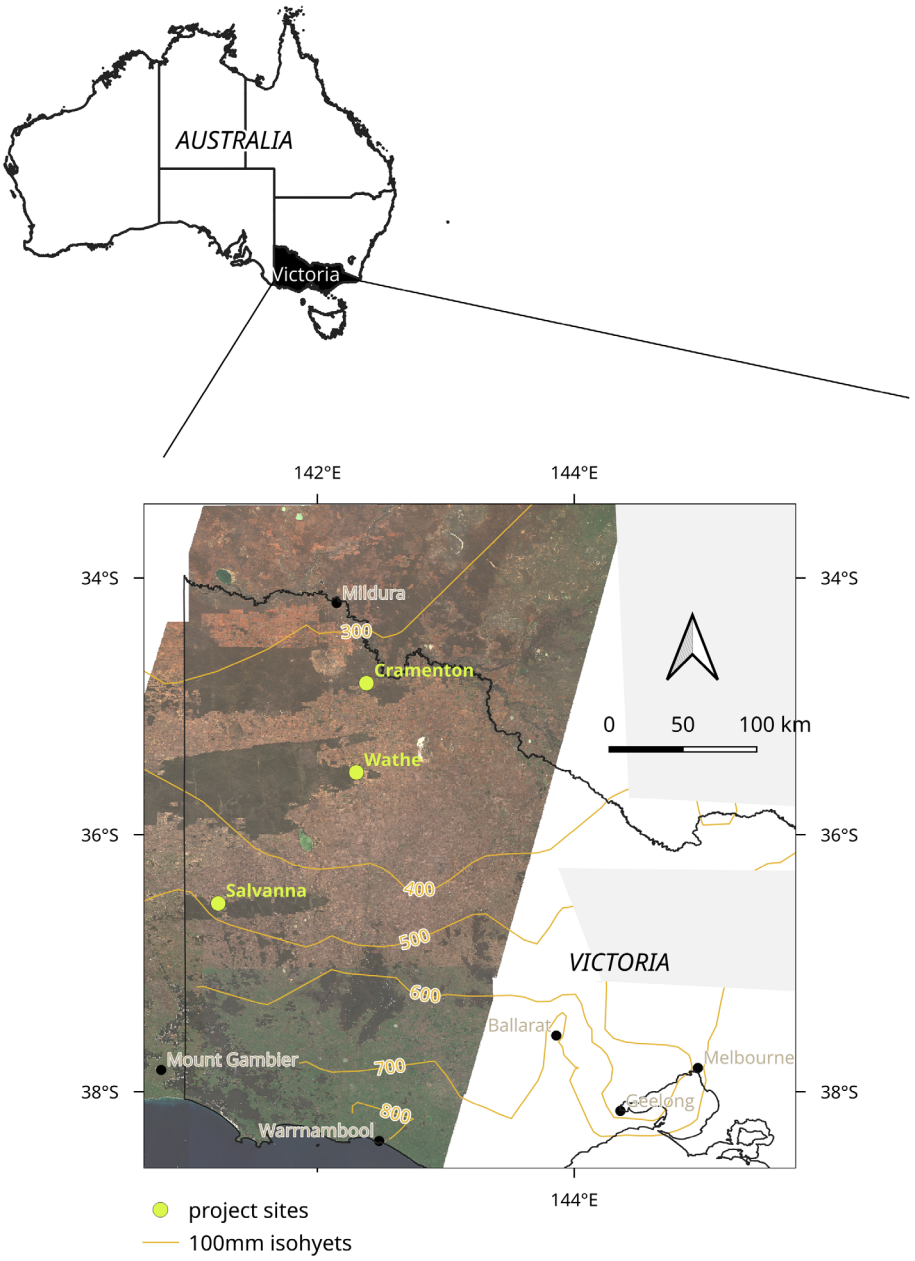


Figure 1. Location of study sites in north-west Victoria, Australia. Map created by Michael McBain.

came in the form of small biodegradable granules. The microbial inoculant was *Bactivate5* granules, hereon simply referred to as bactivate, which consisted of a blend of five *Bacillus* bacteria on a carbon base. This product was sourced from the Bactivate Company, who originally designed it for agricultural use.

On the 23rd and 24th of May 2023, for Sites 1 and 2, and the 21st of June 2023, for Site 3, the sites were direct-seeded using a *Burford Tree Seeder* (Fig. S1). Each Site had four plots randomly distributed across them, being 50×60 m^2 in size and containing 14 direct seeding lines which were 50 m in length and placed across the plots (Fig. S2). If planting lines were already present from other *Greening Australia* work, the plots were constructed to conform to the shape of these lines (Figs. S3–S5). The direct seeding lines were seeded with four native seeds and one of seven different treatments, with two of each treatment per plot. The treatments used in the study were no treatment (control), fertilizer, hydrogel, bactivate, fertilizer + hydrogel, bactivate + hydrogel, and fertilizer + bactivate. These rows were randomly distributed within the plots.

The seed species used in the study were *Acacia ligulata*, *Callitris gracilis*, *Eucalyptus calycogona*, and *Melaleuca lanceolata*. These species were chosen as they had their germination biology studied in a previous experiment (Stapleton et al. 2024a). Viability tests had been previously performed on

the seeds using a cut test to observe whether the seed embryos were viable. A 1% (w/v) tetrazolium test was then performed by covering the seed embryo with 1% (w/v) triphenyl tetrazolium chloride for 24–48 hours, depending on species, and observing for embryo staining, which indicates a viable seed. *Acacia ligulata* seeds had an average viability of 93%, *E. calycogona* of 92%, *M. lanceolata* of 89%, and *C. gracilis* of 33%. Prior to sowing, *A. ligulata* seeds were treated with recently boiled water to remove seed dormancy (Erickson et al. 2016). All the species were mixed together in a seed mix which contained equal weights of all four species; this was then applied at a rate of 25 g/100 m seeding line. The treatments were placed in the rear seed hopper of the *Burford Tree Seeder*, which allows the soil amendments to be applied at the same time as the seeds (Fig. S1b). The soil amendments were applied at a rate of 40 g/100 m for single treatments, while combined treatments were applied at a rate of 80 g/100 m (40 g + 40 g). These rates were based on the application rates used by *Greening Australia* during their standard revegetation work.

Monitoring

Plots were monitored every 6–8 weeks starting in June 2023 and ending in June 2024 to check for the number of emerging plants along the direct seeding rows. Only one of the four plots at each site was monitored in full (referred to as "full plots"), which included plots 1, 7, and 12. The other plots had their rows divided into three 5 m subsections placed randomly along the rows, which were monitored for seedlings (referred to as "transect plots"). The location of each seedling along the 5 m transects was recorded by measuring the transect and noting the seedlings' position.

During each visit, a measurement of soil moisture in the top layer of the soil was made from the center of each plot using a *MPKit-406B* soil moisture probe from ICT International. During one of the monitoring trips, three soil samples from random locations within each plot were taken and sent to the Cuming Smith British Petroleum and Farmers Limited (CSBP) Soil and Plant Analysis Laboratory, Bibra Lake, Western Australia, for analysis. Soil values were then averaged across each plot.

Data Analysis

The two main variables analyzed were the total emergence count and seedling survival. Survival of the seedlings was worked out by determining at which monitoring trip each individual seedling appeared using the seedling's location data, and then determining at which monitoring trip the seedlings were no longer present. This provided an approximation of how long the seedlings were present. Survival analysis was only performed on the transect plots as location data was not recorded during full plot surveys.

Due to the non-normal distribution of the data, non-parametric tests were used during analysis. A Kruskal–Wallis test was used to test for significance between emergence numbers and the independent effects of the treatments and the site and plot location. A Dunn's test and boxplot were then used to examine the results further. Full plots were analyzed separately from transect plots as the full plots would likely skew results due to the greater number that would be counted using that method. A Kruskal–Wallis test was also performed on the number of days a seedling was present in a plot (survival). In addition, a Kaplan–Meier curve was also constructed using the survival data to help visualize the survival rate of the seedlings.

To analyze the effect of soil variables, a Spearman's correlation was used to determine whether there was a correlation between the measured soil variables and both emergence and survival results. Due to the soil results being averaged for the whole plot, the average seedling count and survival time for each plot were also used for analysis. Due to only having two types of soil texture, there were not enough data points to analyze the effect of soil texture.

Data analysis was performed individually for each seed species used in the study, with all data analysis conducted using R, version 4.2.3 (R Core Team 2024).

Results

Site Properties

Temperature and Rainfall. The sowing season initially experienced a wet late autumn and early winter with an average of 57.5 mm rainfall across the three sites (Fig. 2). Temperatures during this time were mild (around 15–20°C daily maximum) and continued to remain cool over the winter period. Rainfall became less frequent from August to November, with a corresponding increase in daily temperature. Starting in late November and continuing until late December and early January, there were periods of high rainfall, with the highest being 48 mm in 1 day at Site 3. The temperatures were also high at this time, commonly reaching the high 30s. Following this, from late January to early March, temperatures were frequently higher than average with a maximum of 42.8°C reached at Site 3. Temperatures began to cool later, with light rainfall around the end of the study period. Overall, Site 3 experienced the coolest temperatures and highest rainfall with an average maximum temperature of 21.9°C and a total rainfall of 479.4 mm across the experiment. Site 1 experienced the driest conditions with an overall rainfall of 359.2 mm, while Site 2 had the highest temperatures with an average maximum temperature of 24.3°C.

Soil Moisture. Volumetric soil moisture (VSM) began with an average of 6.05% from July to September before dropping to 0% by October (Table 1). There was an increase during November coinciding with an increase in rain across the study area, with an average of 10.1% VSM across all sites. After this event, VSM dropped to zero until June, when it increased to an average of 6.9%. Site 1 experienced the highest VSM values with an average of 5.5% VSM across the study, and plot 2 had the highest VSM with an average of 7.5% VSM and a maximum of 29.1% reached during November. Site 3 had the lowest soil moisture with an average VSM of 1.9%, and plot 11 had the lowest overall with an average of 1.1% VSM.

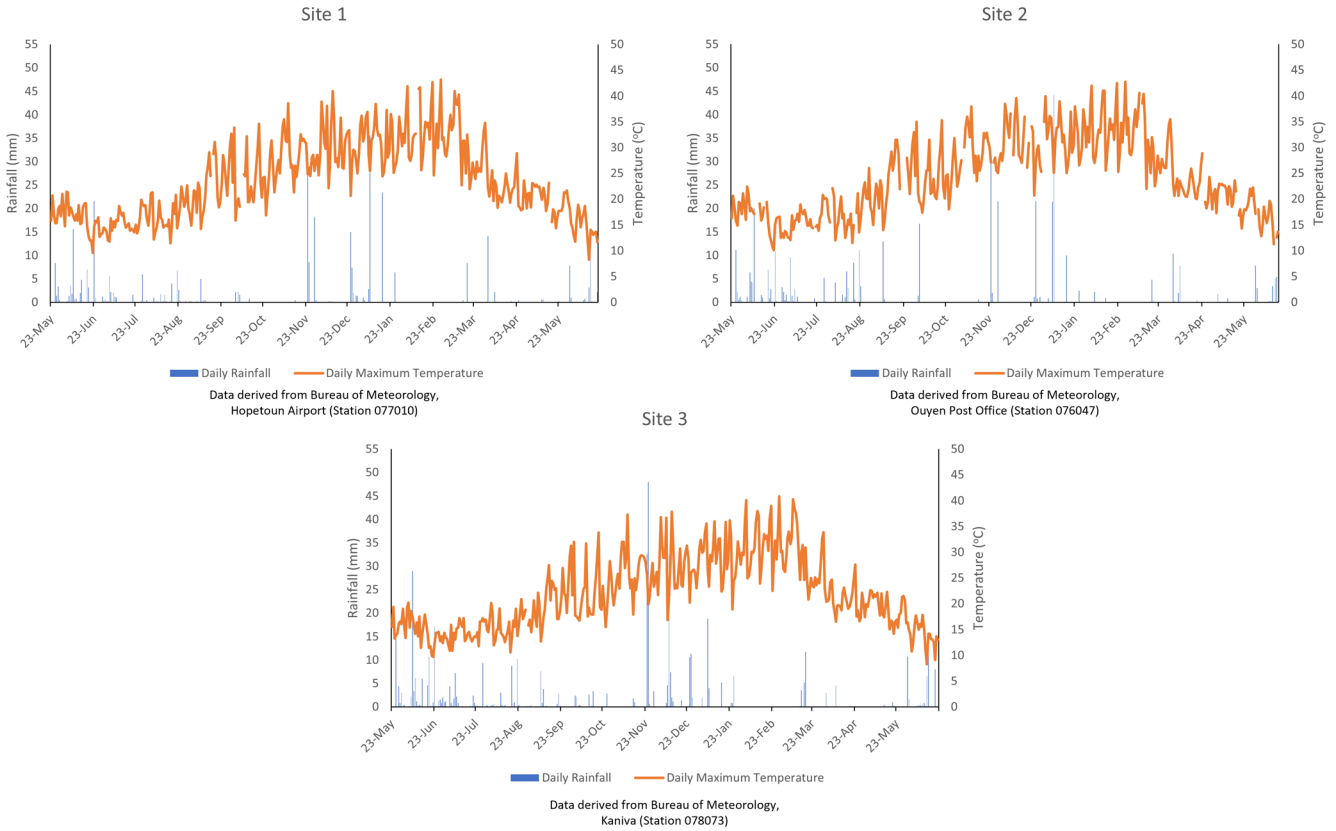


Figure 2. Daily rainfall and maximum daily temperature of all three sites across the study period derived from the Bureau of Meteorology (2024).

Table 1. Volumetric soil moisture (VSM) % across the sites and plots during the study period.

Site no.	*Plot no.*	*25 July 2023*	*13 September 2023*	*31 October 2023*	*29 November 2023*	*31 January 2024*	*13 March 2024*	*1 May 2024*	*20 June 2024*	*Mean*
1	1	4.6	5.4	0	11.6	0	0	0	10.2	4
1	2	5.2	8.7	0	29.1	0	0	0	16.6	7.5
1	3	5.2	6	0	13.8	0	0	0	10.5	4.4
1	4	9	8.6	0	19.2	0	0	0	11.2	6
2	5	0	4.3	0	5.4	0	0	0	5.3	1.9
2	6	8.5	9.6	0	13.8	0	0	0	8.4	5
2	7	9.8	8.0	0	13.5	0	0	0	5.8	4.6
2	8	5.5	7.9	0	10	0	0	0	5.8	3.7
3	9	5.7	4.7	0	0	0	0	0	4.5	1.9
3	10	9.1	4.9	0	4.7	0	0	0	4.9	3
3	11	4.9	4	0	0	0	0	0	0	1.1
3	12	5.1	4.7	0	0	0	0	0	0	1.2

Soil Properties. The soil at the study sites had a sandy-loam to sandy texture with low nutrient levels and organic matter (Table S1), as is typical for the region. Site 1 had the overall highest concentrations of phosphorous, potassium, and sulfur. This was particularly evident in plot 2, which had the highest levels of phosphorous, potassium, ammonium nitrogen, and conductivity, as well as having the highest gravel percentage. Site 3 had the overall lowest level of nutrients, as well as being the sandiest site and having the most acidic pH. Plot 9 was particularly notable in having the lowest potassium and conductivity, as well as the second lowest sulfur and equal lowest nitrate nitrogen, ammonium nitrogen, and phosphorous levels. However, Site 3 also had the overall highest organic carbon concentration and slightly higher ammonium nitrogen concentrations than the other sites. While the properties of the soil at Site 2 were mostly intermediate between the two other sites, the site did have overall lowest organic carbon and ammonium nitrogen. Of note, plot 5 had a lower gravel percentage and

lower nutrient levels than the other plots at Site 2, which is likely due to its position on the top of a sand dune, which differs from the position of the three other plots, which are positioned on a sandplain.

Seedling Emergence

Total Emergence Count. Only *Acacia ligulata* and *Callitris gracilis* emerged during the study period, with no *Eucalyptus calycogona* or *Melaleuca lanceolata* seedlings being found.

Treatment had no significant effect for either species on the total emergence numbers (Table S2). However, plot and site location did have a significant effect on total emergence numbers across both species (Fig. 3). Site 2, which includes plots 5–8, had the highest emergence counts for both species with a total count of 493 *A. ligulata* and 297 *C. gracilis* seedlings across all surveyed plots. These numbers were significantly greater than both Site 1 and Site 3 for *A. ligulata* and Site 1 for *C. gracilis* (Table S3). Plot 7 had the highest counts of the full plots, with maximum counts of 234 and 124 for *A. ligulata* and *C. gracilis*, respectively. This was significantly greater than the other full plot counts for *A. ligulata*, although the counts were only significantly greater than plot 1 for *C. gracilis* (Table S4). Plot 6 had the highest counts for the transect plots, with maximum counts of 91 for *A. ligulata* and 62 for *C. gracilis*.

The site with the lowest count was Site 1, which includes plots 1–4, with a total count of 117 *A. ligulata* and 141 *C. gracilis* seedlings. The plot with the lowest seedling count was plot 2 with no *A. ligulata* seedlings and only four *C. gracilis* seedlings over the course of the study. An exception to the low Site 1 numbers was plot 3, which had a higher count of both species compared to the rest of the sites, with 88 *A. ligulata* and 56 *C. gracilis* seedlings. In addition, among transect plots, the counts of *A. ligulata* were significantly higher in plots 3, 5, 6, 8, and 10 than in plot 2, with plot 6 also having significantly higher counts than plot 4 (Table S5), which had the second lowest seedling count (eight seedlings). Similarly, for the *C. gracilis* counts, plots 3, 6, 8, and 11 had significantly higher counts than plot 2, with plot 6 again being significantly higher than plot 4.

The only soil parameters that were found to correlate with seedling numbers were ammonium nitrogen, for both *A. ligulata* and *C. gracilis* (Fig. 4), and organic carbon, for *A. ligulata* only. In both cases, an increase in the soil property led to a decrease in the seedling count. The ρ values were strong, with all ρ values being under -0.70.

Seedling Counts Over Time. There was a large decrease in seedling count over the course of the study, with the most notable drop being among the *A. ligulata* seedlings in Site 2, which went from 484 counted seedlings on one monitoring trip to 45 seedlings on the next (Fig. S6). Site 3 appears to have a delayed peak compared to the other two sites, which may be due to it being planted later than the other sites. By the end of the study, there were 16 *A. ligulata* seedlings counted (6 from Site 1, 2 from Site 2, and 8 from Site 3) and 19 *C. gracilis* seedlings (1 from Site 1, 0 from Site 2, and 18 from Site 3). Both of the two seedlings left at Site 2 came from plot 5. At Site 3, 15 out of the 18 *C. gracilis* seedlings were from plot 12.

Seedling Survival

There was no significant effect of soil amendment treatment on the survival time of the seedlings (Table S6).

Both *A. ligulata* and *C. gracilis* showed a decrease in survival over the course of the study (Fig. 5) with a final survival percentage of 2.8 and 4.1%, respectively. *Acacia ligulata* experienced a sharp decline in survival around the 70-day mark (Fig. 5A) and, overall, declined at a quicker rate than *C. gracilis*.

Both plot and site position had a significant effect on the survival times of the seedlings. In terms of site, Site 1 significantly increased the survival time compared to the other sites for *A. ligulata* seedlings, with Site 2 and Site 3 not being significantly different from each other (Fig. 6A). For *C. gracilis*, Site 3 had the highest survival times, which were significantly greater than Site 1 and Site 2, which did not differ (Fig. 6B). Among the *A. ligulata* plots, plot 4 was the overall best performing plot, while plots 6, 8, and 9 were notably poor performing (Fig. 6C) with plot 9 having significantly lower survival times than plots 10, 4, and 3 (Table S7). Plot 6 was also significantly lower than both plots 3 and 4, while plot 8 was only significantly lower than plot 4. For *C. gracilis*, the overall best performing plot appeared to be plot 10 (Fig. 6D), which had significantly higher survival times than plots 9, 8, 6, 5, and 4 (Table S8). Plot 11 also had significantly higher survival times than plots 6 and 4, while plot 3 performed significantly better than only plot 4.

The only soil properties to have a significant correlation with seedling survival time were ammonium nitrogen, for *A. ligulata*, and nitrate nitrogen, for *C. gracilis* (Fig. 7). Increases in ammonium nitrogen were found to strongly correlate with an increase in *A. ligulata* survival time (ρ value $= 0.82$) while increases in nitrate nitrogen were found to correlate with decreases in *C. gracilis* survival times (ρ value $= 0.88$).

Discussion

Species Response to Direct Seeding

Of the four species planted for the study, only two of the species, *Acacia ligulata* and *Callitris gracilis*, successfully emerged from the direct seeding plots. No seedlings from *Eucalyptus calycogona* or *Melaleuca lanceolata* were recorded during monitoring. One of the notable differences between species which did emerge and those which did not was the seed size. Both *E. calycogona* and *M. lanceolata* had relatively small seeds, while the seeds of *A. ligulata* and *C. gracilis* were significantly larger. These results are similar to other studies which have also found that larger seeded species were more successful under direct seeding methods (Palma & Laurance 2015; Ceccon et al. 2016). This may be due to larger seeds having greater nutritional reserves to draw upon (Bond et al. 1999) buffering them against environmental factors such as dry weather (Hallett

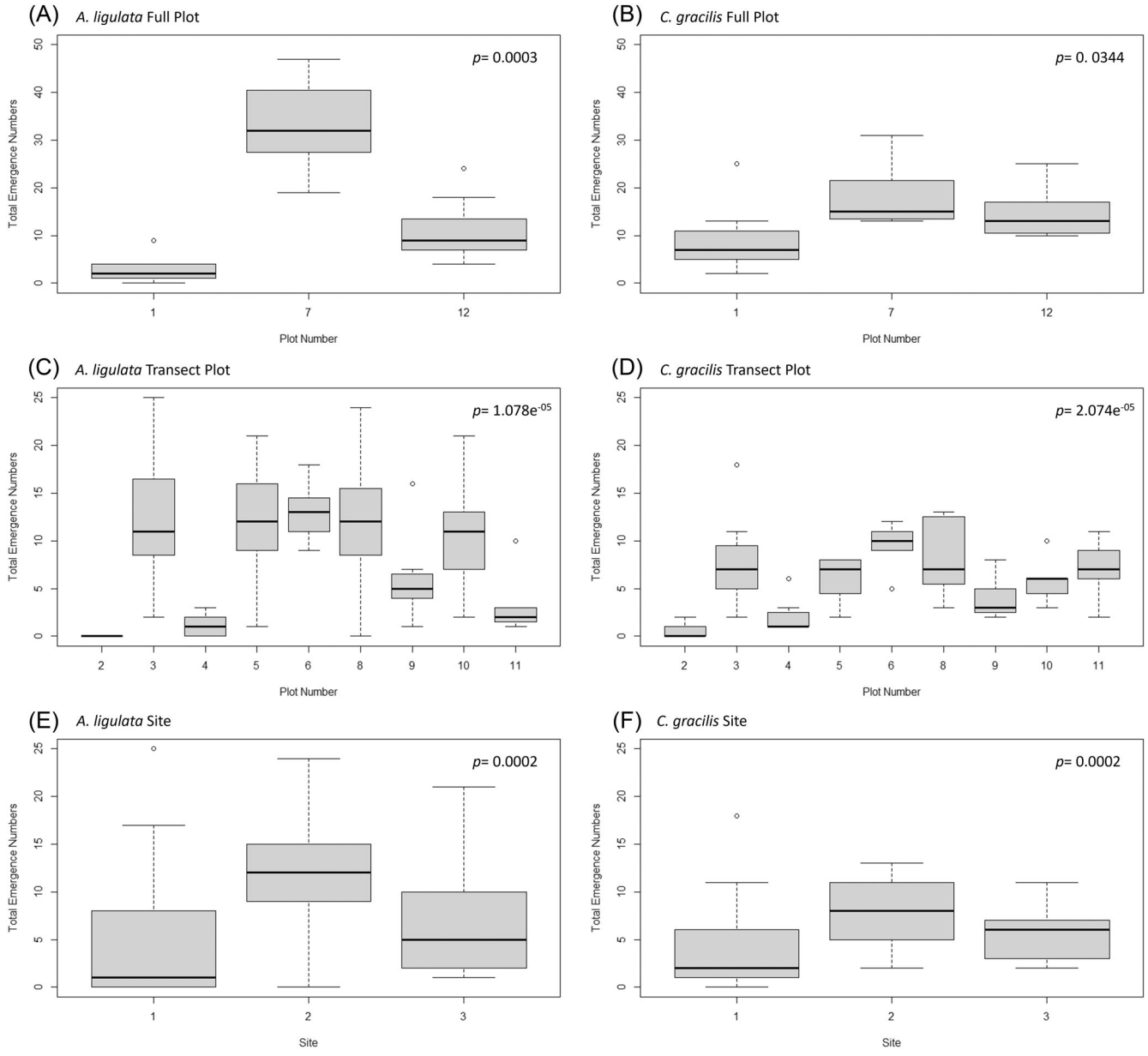


Figure 3. The effect of plot (A–D) and site (E–F) on seedling count.

et al. 2011). Conversely, a previous study examining the germination biology of the same four species used in this study under laboratory conditions found that *E. calycogona* and *M. lanceolata* preferred warmer germination temperatures and tolerated drier conditions better than the larger-seeded species (Stapleton et al. 2024a). Although a follow-up study found that, when the seeds were buried in soil, even though they all emerged, the lighter seeded species were more heavily affected by low water conditions (Stapleton et al. 2025). This indicates that the addition of soil brings additional factors that affect the germination of seeds (El-Keblawy et al. 2018). It also indicates that, since *E. calycogona* and *M. lanceolata* are able to emerge after being buried, other factors are affecting them in the field, such as weed competition or possibly the mechanism of direct seeding itself, which may not be suitable for these seeds. Another possible factor is that since the seeds were seeded during late autumn to early winter, the temperature may not have been suitable, and sowing during warmer seasons may be more preferable for *E. calycogona* and *M. lanceolata* (Stapleton et al. 2024a).

Of the two species that did germinate, *A. ligulata* overall produced the most seedlings and emerged quicker than *C. gracilis*. This corresponds with other studies which indicate that *A. ligulata* is a good colonizer of disturbed environments (Onans & Parsons 1980) and is particularly well adapted to sandy soils which predominate across the study sites

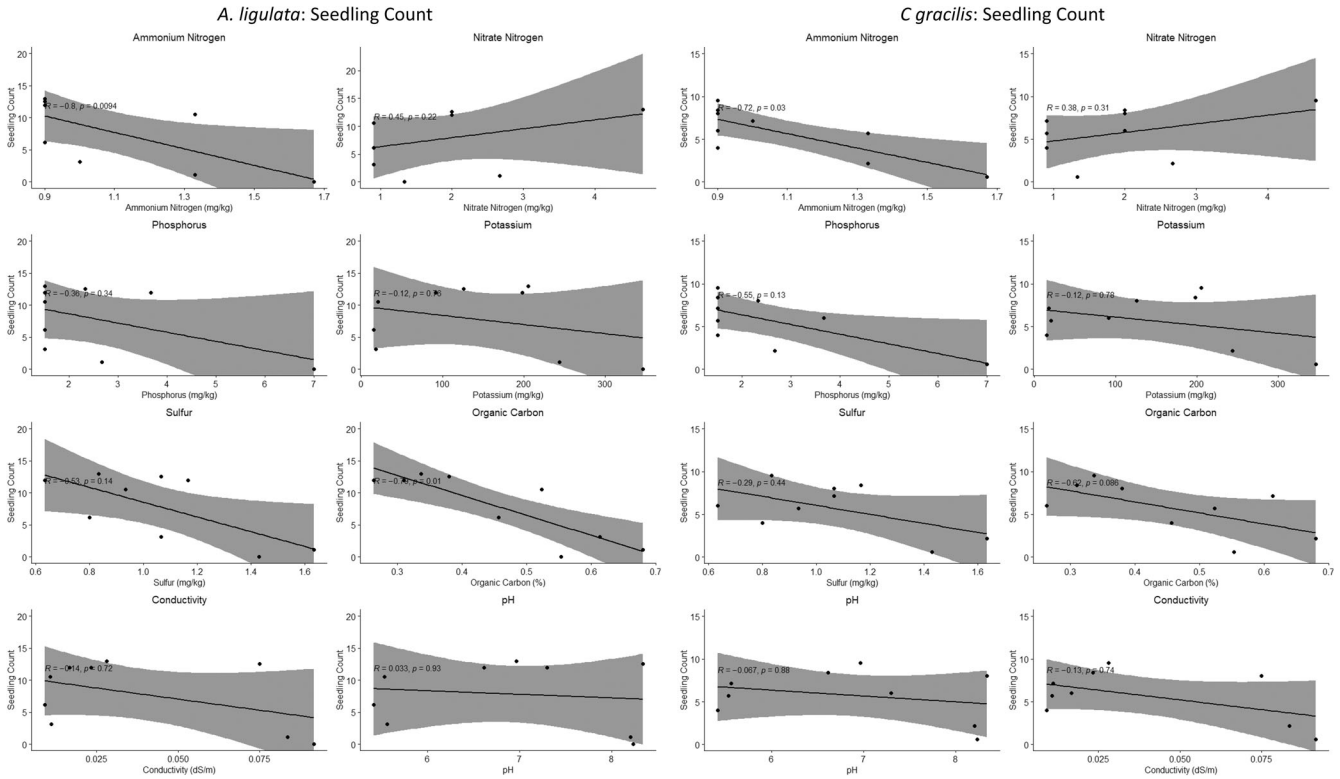


Figure 4. Correlation between soil parameters and seedling count for (A) *Acacia ligulata* and (B) *Callitris gracilis*.

(Chapman & Maslin 1992). Another potential contributing factor is that the *A. ligulata* seeds were treated with recently boiled water before being planted in order to break seed dormancy. This would have significantly increased their ability to germinate and emerge, as was found by another study by Mayence et al. (2017), which showed that dormancy-alleviated *A. ligulata* seeds emerged at a 41 times greater rate in the field than seeds which were not treated beforehand. Despite this large initial emergence, *A. ligulata* seedlings also died off quickly, with seedling numbers almost dropping by 50% between the July and September monitoring events. These results are similar to a study by Denham and Auld (2004), which found that of over 700 seedlings surveyed during the study, only a few survived beyond 9 months, with the main cause of death being desiccation. The soil moisture data indicates that soil moisture remained low throughout the year, other than after large rainfall events, and would quickly drop, especially during the warmer months. This may have had a negative impact on *A. ligulata* seedlings, with the species initially germinating well after dormancy-breaking treatments, and then dying off once soil moisture was not found to be adequate. Another contributing factor could have been grazing pressure. *Acacia ligulata* seedlings have been previously shown to be vulnerable to grazing (Munro et al. 2009) and the presence of rabbits and macropods, through scat and signs of activity such as footprints and rabbit diggings, were noted at all sites (with Site 1 having the most signs). Grazing damage was also noted on many of the seedlings during the study, with grazing being heaviest at the end of the experiment, which produced a notable decrease in height and width of seedlings during the last monitoring event. However, the majority of the seedlings had already died off at this time, making it unlikely to be the sole reason for the drop in seedling numbers.

Callitris gracilis had overall lower numbers than *A. ligulata* and germinated slower, which matches up with a previous germination biology study that also found the species was slow to germinate under ex situ conditions (Stapleton et al. 2024a). The species also died off at a slower rate, reaching 50% decline in numbers after 4 months rather than 3, as in *A. ligulata*, and had a higher final count of 19 compared to *A. ligulata's* 16, though most of these were from a single plot (plot 12). An important factor for *C. gracilis* germination and survival was likely the weather conditions during the study. *Callitris gracilis* is a cool-climate germinator that prefers to hold off germination until cool and wet conditions prevail (Stapleton et al. 2024a). The rainfall and cool temperatures during the planting period would have been within the species preferred germination conditions, helping cause the initial pulse of emergents. A study by Kenny and Moxham (2022) also found that initial *C. gracilis* recruitment was triggered by above-average rainfall, further illustrating the need for wet conditions for this species.

Soil Amendments Have No Effect on Emergence or Survival

None of the soil amendments had an effect on either seedling emergence or survival time for both of the emerging species,

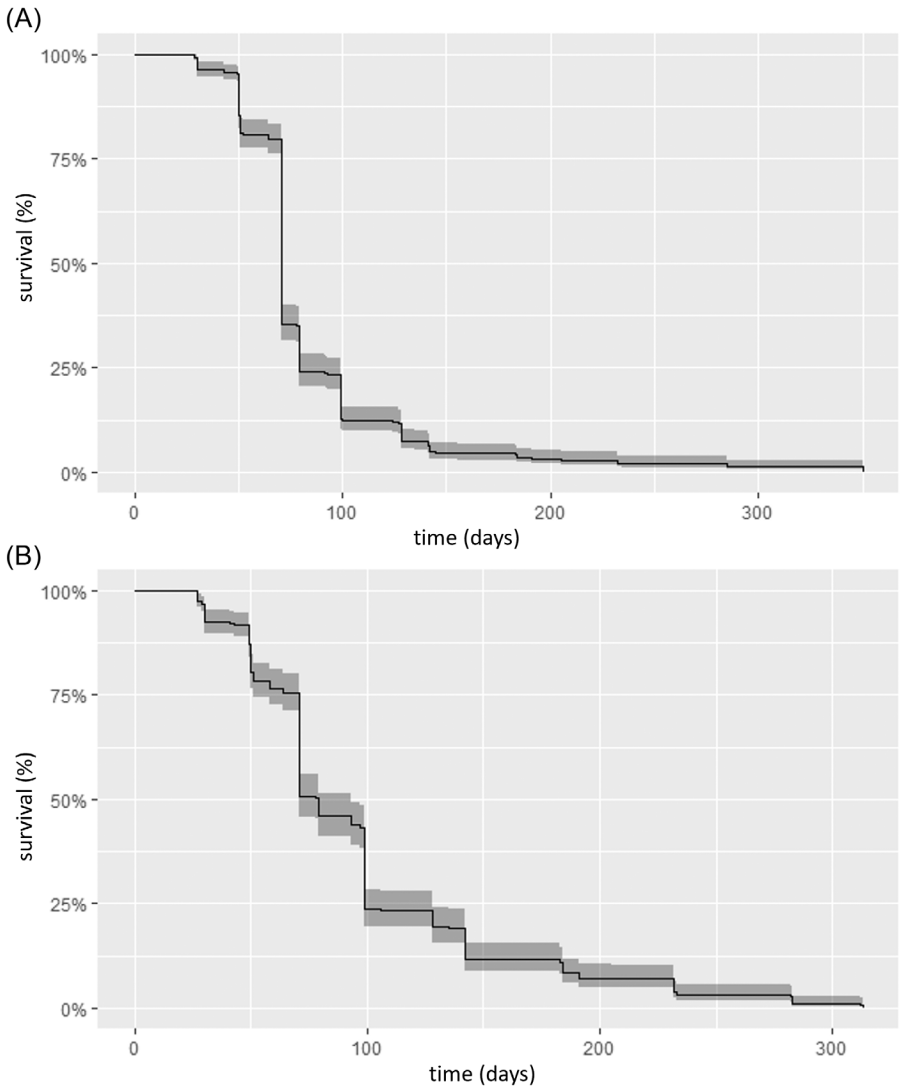


Figure 5. Kaplan–Meier survival curves for (A) *Acacia ligulata* and (B) *Callitris gracilis*.

whether applied singly or in combination. The neutral effect of the amendments on seedling emergence was expected, as a previous glasshouse study using the same species and amendments also found that the amendments had no effect on emergence (Stapleton et al. 2025). However, this field study also indicates that, at least under these circumstances, the amendments also have no effect on survival. These results are contradictory to some other studies which have found that hydrogels can improve seedling survival (Chirino et al. 2011; Minnick & Alward 2012), though other studies have also found the same neutral effect with hydrogels (Commander et al. 2013; Araujo & Pérez 2023). Research, which has gone into microbial inoculants using *Bacillus* bacteria, the same kind used in *Bactivate*, suggests they may be able to increase seedling resistance to stress (Linnett & Uma 2024). Although we did not test for individual seedling stress, the neutral effect on survival suggests there was no advantage to *Bacillus* inoculation in this study. Fertilizers have previously been found to produce a negative or neutral result due to their probable negative effect on drought tolerance (Trubat et al. 2011). This study found no positive effects, though there were no negative effects on survival either, suggesting that they were not having a detrimental impact on seedlings and instead were neutral in effect.

Seedling Location Has the Greatest Effect on Emergence and Survival

The strongest factor affecting both seedling growth and survival was their plot and site location. For seedling emergence, plots 6–8 from Site 2 had the highest emergence numbers for both *A. ligulata* and *C. gracilis*, with all three of these plots being located along a flat sandplain at the base of a dune system. Other plots with notably high emergence numbers were plot 3 from Site 1, plot 5 from Site 2, and from Site 3, plot 10 for

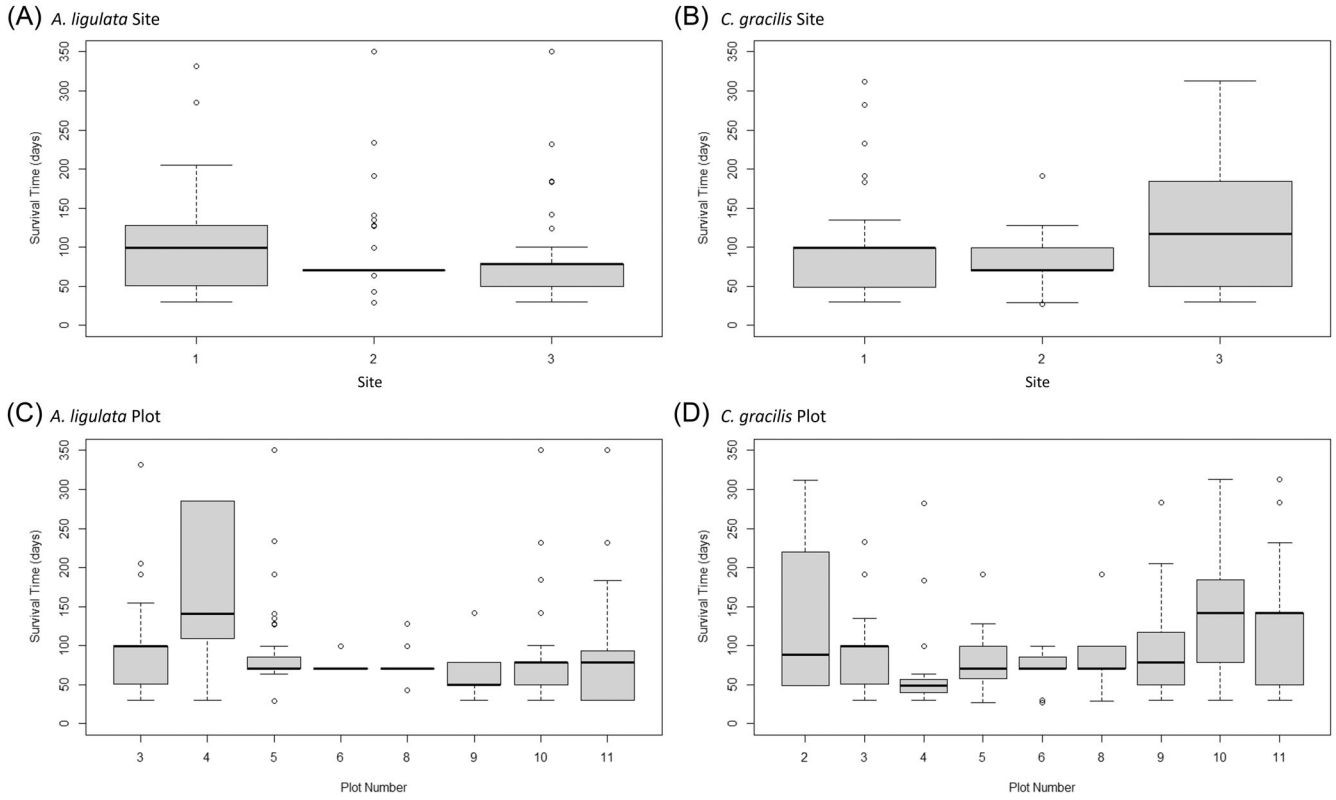


Figure 6. The effect of site (A and B) and plot (C and D) on seedling survival time (days).

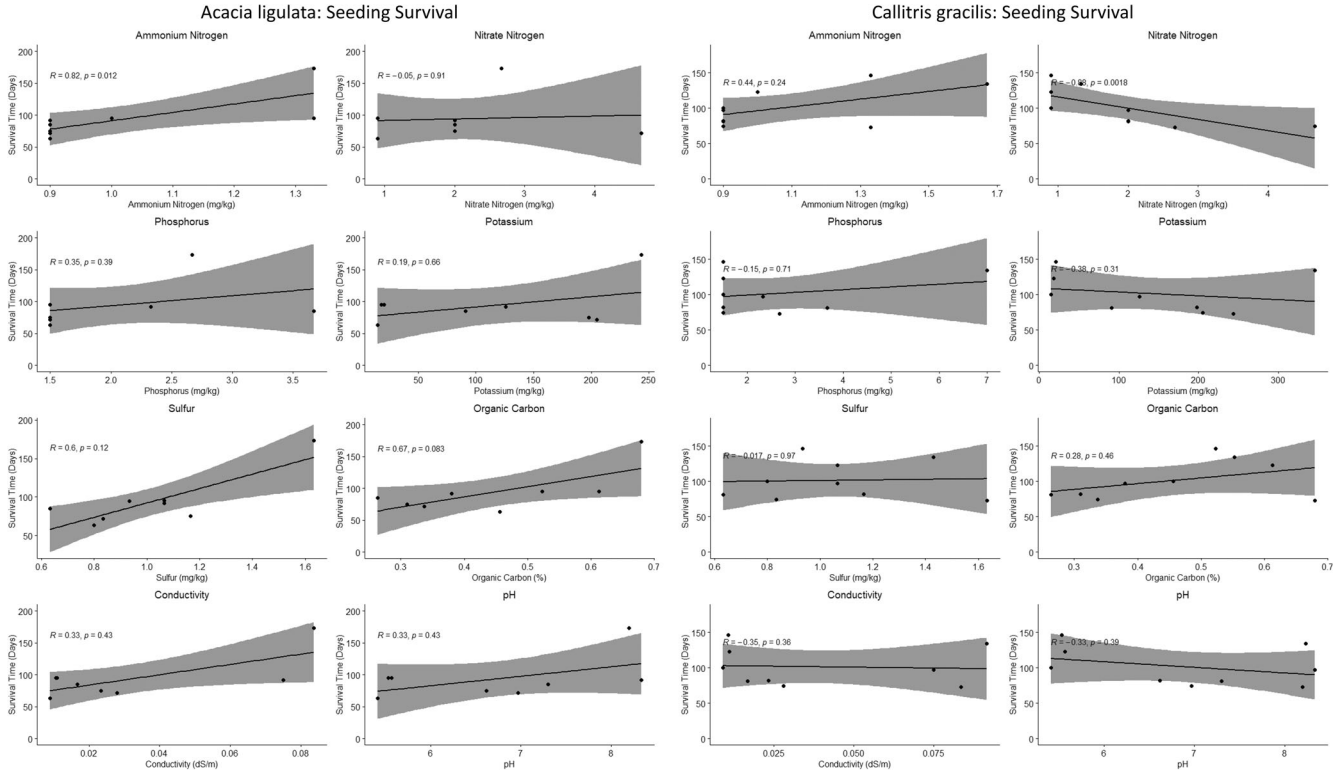


Figure 7. Correlation between soil parameters and seedling survival for (A) *Acacia ligulata* and (B) *Callitris gracilis*.

A. ligulata and plots 11 and 12 for *C. gracilis*. These plots generally had low nutrient levels, particularly for potassium, and plot 3 was notably located in a sandier area on top of a sand dune compared to the rest of Site 1. Following on from this, emergence was correlated with low soil ammonium nitrogen levels and low organic carbon and declined as these attributes increased. Plots 6–8, in particular, all share a similar soil type characterized by low organic carbon and low nutrient concentrations of ammonium nitrogen. This preference for low nitrogen is further reinforced by plot 2 having the lowest emergence counts, with no *A. ligulata* seedlings and only four *C. gracilis* emergents, while also having the highest overall ammonium nitrogen levels of the whole project. It should also be noted that the soil here had a harder surface and had a higher moisture content, which may have also prevented seedlings from emerging. *Acacia ligulata* has been previously noted to specialize in low nutrient sand dune environments (Chapman & Maslin 1992), which may explain its preference for low nitrogen and organic matter levels. Similarly, *Callitris* species have also been found to have a preference for low nutrient soils, such as shallow sands (Adams 1982), and therefore would also be expected to germinate better in these low nutrient plots. Another factor that might be at play is the weed competition across the plots. In general, weeds are more likely to colonize and persist in high nutrient areas (Prober & Wiehl 2011), which then compete with native seedlings for resources (Clarke et al. 2005). This effect may have been present, at least in Site 1, where weed densities were noted to be high at plots 1 and 2, which had lower seedling emergence counts than plots 3 and 4, which appeared to have much lower weed densities.

Seedling survival was also strongly affected by the site and plot position, though the best performing locations differed from emergence. Despite their initial high emergence, the seedlings at plots 6–8 died off quickly after they peaked with a 93% drop in numbers between the peak and the next monitoring event and no seedlings left by March 2024. The landholders noted that this area was cropped in the past, but all the crops failed to survive to maturity, indicating there may be some aspect to the soil here that was not picked up in the soil analysis which was influencing the plant emergence and survival. *Acacia ligulata* and *C. gracilis* showed different responses to survival based on location. For *A. ligulata*, Site 1 contained the longest surviving seedlings with plot 4, followed by plot 10 from Site 3 being the best performing. For *C. gracilis*, Site 3 performed best with plot 10, followed by plot 11 having the longest surviving seedlings. The effect of soil on survival also differed from emergence count. For *A. ligulata*, an increase in ammonium nitrogen increased survival time, while for *C. gracilis*, an increase in nitrogen nitrate decreased it. This all indicates that the soil and site properties that govern survival likely differ from those that influence emergence. The results from *A. ligulata* seem to suggest that higher nitrogen levels may be better for survival; however, the addition of fertilizer had no effect on emergence or survival. Previous studies have also shown that *Acacia* species receive no survival benefit from fertilizers (Hosseini Bai et al. 2014), which makes the survival preference seem unusual. It is possible that some other factor was influencing survival at the plots where survival was highest, with the correlation with soil nutrient simply being a by-product. It was observed that grazing pressure was an issue during the study, particularly in its later stages, so it may be that the two plots had lower grazing pressure. The seedlings at plot 4 were also noted to be the largest during the study, indicating there was some benefit for growth that may have also assisted with survival since larger plants are able to build up more of a nutrient reserve, which can aid in survival (Oliet et al. 2009). For *C. gracilis*, its survival correlation with low nitrate nitrogen is reflective of its preference for Site 3, which had the lowest nitrate nitrogen levels. This may indicate it prefers these soil conditions, though it should also be noted that this site had the highest rainfall, lower temperatures, and, even though the soil did not hold on well to the moisture, the wetter and cooler conditions may have been more preferential for this species, as these conditions have previously been shown to be beneficial to *C. gracilis*, at least at early stages of a seedling's life (Kenny & Moxham 2022; Stapleton et al. 2024a). Two exceptions to this trend were plot 2 from Site 1 and plot 9 from Site 3. Plot 2 had higher survival times, though this was represented by one seedling with low emergence results since this plot also had higher soil moisture that may have helped keep the seedlings alive. Plot 9, which was at Site 3, had low survival results. The plot was located on the side of a dune that faced the midday sun, which could have led to higher temperature and water stress compared to the rest of the site.

Restoration and Future Research Recommendations

Based on the results of this study, the three soil amendments used (hydrogels, fertilizers, and microbe inoculants) had no effect on emergence or survival, and hence would appear to be not worth adding to future plantings. However, it should be noted that the dosage used during the trial was only 40 g/100 m, and it is possible that a higher dosage might produce a more notable effect. In particular, combinations of the amendments often performed better than single treatments or control, although the effect was not significant. Future trials using higher dosages might help ascertain whether an effect is possible.

The failure of the small-seeded *E. calycogona* and *M. lanceolata* to emerge indicates that these species may not be fit for direct seeding work. Given that other studies have also found poorer results for small-seeded species during direct seeding (Palma & Laurance 2015; Ceccon et al. 2016), it may be better to use a mixed approach (Ceccon et al. 2016; Araujo & Pérez 2023) where the small-seeded species are hand-planted and the larger seeds are direct seeded, an approach that is already commonly undertaken by practitioners in these low rainfall areas. Alternatively, it may also be worth seeing if changing the time of direct seeding to warmer seasons improves the emergence of *E. calycogona* and *M. lanceolata* as they may be species that prefer to germinate under warm conditions (Stapleton et al. 2024a). Of the species that did germinate, *A. ligulata* experienced greater emergence while *C. gracilis* had higher survival times. Though both species experienced large die-off over the course of the study, being especially sharp in *A. ligulata*, likely

coinciding with a decrease in rainfall frequency and an increase in temperature during the spring. Overall, the direct seeding work would be considered a failure for this particular study given the low survival rates. A possible way to reduce the die-off rate of *A. ligulata* could be to sow both seeds treated to break dormancy and untreated seeds to allow a mix of quick-germinating seeds and seeds that will stall development if conditions are not right, spreading the risk of failure over a longer timescale (Mayence et al. 2017), a tactic that is already used in many direct seeding revegetation works.

Location had the largest effect on both emergence and survival of seedlings. However, the soils that produced the highest emergence numbers did not have the highest survivorship, suggesting that different factors affect emergence and survival. Therefore, follow-up monitoring is critical to fully understand a project's success. Also, although low nitrogen levels produced high initial emergence, they did not correlate with survival. A reason for this trend is likely due to the high emergence followed by poor survival of seedlings within plots 6–8 characterized by low nutrient sand plains suggesting that these environments may be particularly challenging for direct seeding work. Both species appear to survive better on the sand dunes than the sand plains. *Acacia ligulata* also showed a correlation between higher nitrogen and better survival suggesting that this species may be more resilient to soils enriched by previous agricultural use. *Callitris gracilis* survival showed a preference for low nitrogen levels suggesting that this species might do better planted in less disturbed environments. In particular, *C. gracilis* survived best in the low nutrient, sandy soils of Site 3 implying this soil type is closer to its preferred growing conditions. It should be noted that this site also had cooler temperatures and higher rainfall and, given *C. gracilis'* preference for germination under cool wet weather (Kenny & Moxham 2022; Stapleton et al. 2024a), this may have also had an impact. Regardless, the low survival rate of both species coming into spring suggests that early survival is likely highly reliant on spring rainfall, which was not being provided by the relatively dry spring of the study period.

Research Limitations

The results of this study are limited to the species and landscapes tested. While some extrapolation can be made on related species and direct seeding as a whole, caution should be taken as different species will have different responses to direct seeding (Suieiman et al. 2023). The effect of soil amendments may also change based on soil type or climate. For example, hydrogels may not work well under extremely dry conditions (Commander et al. 2013) as there will be limited moisture to recharge.

This study only measured soil moisture in the top few centimeters of the soil, with no information being recorded on the moisture deeper into the soil profile. It is highly likely that the emerging seedlings would have grown their roots down to access deeper moisture, which may have played a role in their survival.

It is also suspected that weed competition and grazing damage had a strong effect on seedling emergence and survival (Munro et al. 2009; Passaretti et al. 2020), although these effects were not officially measured as part of this study. High weed densities were noted at plots 1 and 2, and grazing damage was noted to be high toward the end of the study, particularly at Site 1.

Acknowledgments

This work was supported by *Greening Australia* and Federation University Australia through funding as part of the PhD project of Joseph Stapleton. Thanks also go to *Greening Australia* for performing the direct seeding work and helping to set up the monitoring sites, with particular thanks going to J. Gardner for assisting in the site setup, and S. Bates who assisted with surveying the plots. A number of Federation University students assisted in the field surveys, to whom thanks are recorded. They were: T. S. Arachchige, E. Popham, J. Werner, A. E. S. Patrick, C. Hosking, B. McPhee, S. Gannon, and M. Lalor. Thanks are also due to N. Robinson from Federation University, who provided valuable advice on the methodology for collecting soil samples. T. Mayr from the Department of Energy, Environment and Climate Action helped with the application for a research permit to work on public land, which was necessary for Site 1. J. Douglas from the Mallee Catchment Management Authority (CMA) assisted with determining plot locations at Site 2 since he had previously worked there. Special thanks also go to Trevor and N. Hinton for allowing us to perform part of the field trials on their property at Site 2 and for providing information on the conditions and history of the field trial site. M. McBain created the map of the project area seen in Figure 1. The CSBP Soil & Plant Laboratory performed analysis on soil collected from the field trial sites so that the information could be used to help interpret results. Open access publishing facilitated by Federation University Australia, as part of the Wiley - Federation University Australia agreement via the Council of Australian University Librarians.

LITERATURE CITED

Adams R (1982) Aspects of the distribution and ecology of two species of Callitris vent. Victoria. Unpublished PhD thesis. LaTrobe University, Melbourne, Victoria, Australia.

Araujo MER, Pérez DR (2023) From seed germination to established seedlings: a comparative evaluation in five shrub species and implications for seed-based restoration in arid lands. Restoration Ecology 31:e13862. https://doi.org/10.1111/rec.13862

Azizi S, Tabari M, Abad ARFN, Ammer C, Guidi L, Bader MKF (2022) Soil inoculation with beneficial microbes buffers negative drought effects on biomass, nutrients, and water relations of common Myrtle. Frontiers in Plant Science 13:892826. https://doi.org/10.3389/fpls.2022.892826

Bond WJ, Honig M, Maze KE (1999) Seed size and seedling emergence: an allometric relationship and some ecological implications. Oecologia 120:132–136. https://doi.org/10.1007/s004420050841

Bureau of Meteorology (2024) Climate data online. http://www.bom.gov.au/climate/data/ (accessed 06 Nov 2024)

Ceccon E, González EJ, Martorell C (2016) Is direct seeding a biologically viable strategy for restoring forest ecosystems? Evidences from a meta-analysis.

Land Degradation and Development 27:511–520. https://doi.org/10.1002/ldr.2421

Chapman A, Maslin B (1992) Acacia miscellany 5. A review of the *A. bivenosa* group (Leguminosae: Mimosoidea: Section Phyllodineae). Nuytsia—The journal of the Western Australian Herbarium 8:249–283. https://doi.org/10.58828/nuy00179

Chirino E, Vilagrosa A, Vallejo VR (2011) Using hydrogel and clay to improve the water status of seedlings for dryland restoration. Plant and Soil 344: 99–110. https://doi.org/10.1007/s11104-011-0730-1

Clarke PJ, Latz PK, Albrecht DE (2005) Long-term changes in semi-arid vegetation: invasion of an exotic perennial grass has larger effects than rainfall variability. Journal of Vegetation Science 16:237–248. https://doi.org/10.1111/j.1654-1103.2005.tb02361.x

Commander LE, Rokich DP, Renton M, Dixon KW, Merritt DJ (2013) Optimising seed broadcasting and greenstock planting for restoration in the Australian arid zone. Journal of Arid Environments 88:226–235. https://doi.org/10.1016/j.jaridenv.2012.08.012

Copeland SM, Munson SM, Pilliod DS, Welty JL, Bradford JB, Butterfield BJ (2018) Long-term trends in restoration and associated land treatments in the southwestern United States. Restoration Ecology 26:311–322. https://doi.org/10.1111/rec.12574

de Souza Gomes Guarino E, Scariot A (2014) Direct seeding of dry forest tree species in abandoned pastures: effects of grass canopy and seed burial on germination. Ecological Research 29:473–482. https://doi.org/10.1007/s11284-014-1143-4

Denham AJ, Auld TD (2004) Survival and recruitment of seedlings and suckers of trees and shrubs of the Australian arid zone following habitat management and the outbreak of rabbit Calicivirus disease (RCD). Austral Ecology 29:585–599. https://doi.org/10.1111/j.1442-9993.2004.01393.x

El-Keblawy A, Gairola S, Elsheikh EA, Hussain MI, Abhilash P (2018) Variability in seed germination behaviour of six grasses under laboratory and natural field conditions: implications for restoration of degraded lands in subtropical arid deserts. Tropical Ecology 59:715–726

Erickson TE, Merritt DJ, Turner SR (2016) Overcoming physical seed dormancy in priority native species for use in arid-zone restoration programs. Australian Journal of Botany 64:401–416. https://doi.org/10.1071/BT16059

Ewing CP, Catterall CP, Tomerini DM (2013) Outcomes from engaging urban community groups in publicly funded vegetation restoration. Ecological Management and Restoration 14:194–201. https://doi.org/10.1111/emr.12054

Figueiredo MA, Teixeira Braga Messias MC, Praça Leite MG, Kozovits AR (2021) Seed covering and dry periods in the rainy season interfere with direct seeding success in the restoration of post-mined grasslands. Ecologia Austral 31:444–455. https://doi.org/10.25260/EA.21.31.3.0.1446

Hallett LM, Standish RJ, Hobbs RJ (2011) Seed mass and summer drought survival in a Mediterranean-climate ecosystem. Plant Ecology 212:1479–1489. https://doi.org/10.1007/s11258-011-9922-2

Hallett LM, Standish RJ, Jonson J, Hobbs RJ (2014) Seedling emergence and summer survival after direct seeding for woodland restoration on old fields in south-western Australia. Ecological Management & Restoration 15: 140–146. https://doi.org/10.1111/emr.12110

Hosseini Bai S, Blumfield TJ, Xu ZH (2014) Survival, growth and physiological status of *Acacia disparrima* and *Eucalyptus crebra* seedlings with respect to site management practices in Central Queensland, Australia. European Journal of Forest Research 133:165–175. https://doi.org/10.1007/s10342-013-0755-5

Huang L, Wang D, Yao L, Li X, Wang D, Du Q, Zhang Y, Hou X, Guo Y (2019) Primary limitation on vegetation productivity shifts from precipitation in dry years to nitrogen in wet years in a degraded arid steppe of Inner Mongolia, northern China. Journal of Soils and Sediments 19:544–556. https://doi.org/10.1007/s11368-018-2070-8

Kenny SA, Moxham C (2022) Does above-average rainfall stimulate a recruitment pulse in semi-arid woodlands of southeastern Australia? Journal of Vegetation Science 33:e13148. https://doi.org/10.1111/jvs.13148

Linnett NM, Uma GS (2024) Cross talk between PGPR and *Casuarina junghuhniana* on lignite mine soil. Research Journal of Chemistry and Environment 28:57–65. https://doi.org/10.25303/288rjce057065

Mayence CE, Carrick PJ, Van Beem D, Broenland E, Dixon KW (2017) Seed dormancy, soil type and protective shelters influence seedling emergence at Shark Bay, Western Australia: insight into global dryland revegetation. Ecological Management and Restoration 18:156–163. https://doi.org/10.1111/emr.12253

Minnick TJ, Alward RD (2012) Soil moisture enhancement techniques aid shrub transplant success in an arid shrubland restoration. Rangeland Ecology & Management 65:232–240. https://doi.org/10.2111/REM-D-10-00133.1

Moreira-Grez B, Muñoz-Rojas M, Kariman K, Storer P, O'donnell AG, Kumaresan D, Whiteley AS (2019) Reconditioning degraded mine site soils with exogenous soil microbes: plant fitness and soil microbiome outcomes. Frontiers in Microbiology 10:1617. https://doi.org/10.3389/fmicb.2019.01617

Munro NT, Moseby KE, Read JL (2009) The effects of browsing by feral and re-introduced native herbivores on seedling survivorship in the Australian rangelands. Rangeland Journal 31:417–426. https://doi.org/10.1071/RJ08027

Negoita L, Gibbs JP, Jaramillo Díaz P (2021) Cost-effectiveness of water-saving technologies for restoration of tropical dry forest: a case study from the Galapagos Islands, Ecuador. Restoration Ecology 30:e13576. https://doi.org/10.1111/rec.13576

Oliet JA, Planelles R, Artero F, Valverde R, Jacobs DF, Segura ML (2009) Field performance of *Pinus halepensis* planted in Mediterranean arid conditions: relative influence of seedling morphology and mineral nutrition. New Forests 37:313–331. https://doi.org/10.1007/s11056-008-9126-3

Onans J, Parsons RF (1980) Regeneration of native plants on abandoned Mallee farmland in south-eastern Australia. Australian Journal of Botany 28:479–493. https://doi.org/10.1071/BT9800479

Palma AC, Laurance SGW (2015) A review of the use of direct seeding and seedling plantings in restoration: what do we know and where should we go? Applied Vegetation Science 18:561–568. https://doi.org/10.1111/avsc.12173

Passaretti RA, Pilon NL, Durigan G (2020) Weed control, large seeds and deep roots: drivers of success in direct seeding for savanna restoration. Applied Vegetation Science 23:406–416. https://doi.org/10.1111/avsc.12495

Pérez DR, González F, Ceballos C, Oneto ME, Aronson J (2019) Direct seeding and outplantings in drylands of Argentinean Patagonia: estimated costs, and prospects for large-scale restoration and rehabilitation. Restoration Ecology 27:1105–1116. https://doi.org/10.1111/rec.12961

Prober SM, Wiehl G (2011) Resource heterogeneity and persistence of exotic annuals in long-ungrazed Mediterranean-climate woodlands. Biological Invasions 13:2009–2022. https://doi.org/10.1007/s10530-011-0017-8

R Core Team (2024) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Safriel U, Adeel Z, Niemeijer D, Puigdefabregas J, White R, Lal R, et al. (2005) Dryland systems. Pages 623–662. In: Rashid Hassan RS, Ash N (eds) Ecosystems and human well-being: current state and trend. Island Press, Washington, D.C.

Sampaio AB, Vieira DLM, Holl KD, Pellizzaro KF, Alves M, Coutinho AG, Cordeiro A, Ribeiro JF, Schmidt IB (2019) Lessons on direct seeding to restore neotropical savanna. Ecological Engineering 138:148–154. https://doi.org/10.1016/j.ecoleng.2019.07.025

Silva RRP, Oliveira DR, Da Rocha GPE, Vieira DLM (2015) Direct seeding of Brazilian savanna trees: effects of plant cover and fertilization on seedling establishment and growth. Restoration Ecology 23:393–401. https://doi.org/10.1111/rec.12213

Souza DCD, Engel VL (2018) Direct seeding reduces costs, but it is not promising for restoring tropical seasonal forests. Ecological Engineering 116:35–44. https://doi.org/10.1016/j.ecoleng.2018.02.019

Stapleton J, Bates S, Lewis M, Turner SR, Warne D, Florentine S (2024*b*) A global review on arid zone restoration: approaches and challenges. Restoration Ecology 32:e14078. https://doi.org/10.1111/rec.14078

Stapleton J, Turner SR, Warne D, Florentine S (2025). Effects of burial depth, watering regime and soil amendments on the establishment of four arid

zone species. Ecological Management & Restoration 26. Portico. https://doi.org/10.1111/emr.70010

Stapleton J, Turner SR, Warne D, Florentine S (2024*a*) Linking ex situ germination to in situ direct seeding for landscape scale restoration efforts in the semiarid Mallee region of Victoria, Australia. Restoration Ecology 33: e14220. https://doi.org/10.1111/rec.14220

Suieiman MK, Islam MA, Bhat NR, Jacob S, Thomas RR, Sivadasan MT, Elmi AO (2023) Planting methods influence revegetation success of native species in an arid environment. Canadian Journal of Forest Research 53: 677–687. https://doi.org/10.1139/cjfr-2022-0018

Trubat R, Cortina J, Vilagrosa A (2011) Nutrient deprivation improves field performance of woody seedlings in a degraded semi-arid shrubland. Ecological Engineering 37:1164–1173. https://doi.org/10.1016/j.ecoleng.2011.02.015

Wei J, Yang H, Cao H, Tan T (2016) Using polyaspartic acid hydro-gel as water retaining agent and its effect on plants under drought stress. Saudi Journal of Biological Sciences 23:654–659. https://doi.org/10.1016/j.sjbs.2015.08.016

White MD (2006) The Mallee vegetation of North Western Victoria. Proceedings of the Royal Society of Victoria 118:229–243

Supporting Information

The following information may be found in the online version of this article:

Figure S1. Burford Tree Seeder used for direct seeding study plots.
Figure S2. Plot design used in the field trials.
Figure S3. Map of Site 1 showing location of plots and treatment lines.
Figure S4. Map of Site 2 showing location of plots and treatment lines.
Figure S5. Map of Site 3 showing location of plots and treatment lines.
Figure S6. Change in site seedling count over the course of the study (July 2023–June 2024) for (a) *A. ligulata* and (b) *C. gracilis*.
Table S1. Soil characteristics of the study sites.
Table S2. Effect of treatment on seedling count.
Table S3. Effect of site on total seedling count.
Table S4. Effect of plot on total seedling count for fully surveyed plots.
Table S5. Effect of plot on total seedling count.
Table S6. Effect of treatment on seedling survival time.
Table S7. Effect of site on seedling survival time.
Table S8. Effect of plot on seedling survival time.

Coordinating Editor: Stephen Murphy

Received: 20 September, 2024; First decision: 30 December, 2024; Revised: 24 April, 2025; Accepted: 24 April, 2025