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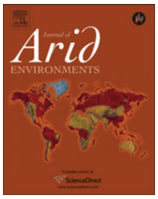

Optimising seed broadcasting and greenstock planting for restoration in the Australian arid zone

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ABSTRACT

Vegetation within some parts of Western Australia has been degraded by resource extraction, and ecological restoration is necessary to prevent erosion and reinstate plant biodiversity. Two restoration approaches, seed broadcasting and planting of seedlings, were tested with plant species (*Acacia tetragonophylla* F. Muell., *Atriplex bunburyana* F. Muell. and *Solanum orbiculatum* Poir.) known to have been dominant prior to mining activities in the World Heritage Area at Shark Bay. For broadcast seeding, soil raking and/or ripping increased seedling emergence, but only after sufficient rainfall. Survival of *A. bunburyana* seedlings (≤92%) was higher than *A. tetragonophylla* (≤13%) almost two years after planting and soil ripping partly alleviated soil impedance and resulted in increased seedling survival. Shoot pruning, fertiliser and moisture retaining gel had a reduced or detrimental effect on survival. Seedling survival differed between the three experimental sites, with electrical conductivity being the most noted soil difference between the sites. Restoration in the arid environs of the World Heritage Area at Shark Bay in Western Australia is challenging, but this study shows that seedling establishment is technically feasible and provides methodology useful to other arid restoration projects.

1. Introduction

Ecological restoration of disturbed landscapes in Western Australia by active return of plant species is necessary due to poor natural recolonisation through seed migration (Standish et al., 2007). In these landscapes, three sources of propagules are available for restoration: respread topsoil (containing a soil seed bank), broadcast seeds and greenstock (nursery generated seedlings).

To optimise seedling emergence, seed broadcasting practices are usually tailored to site conditions and climate. For example, seedling emergence is limited by the number of 'safe sites' for germination (Harper et al., 1965). Safe sites, or 'microsites', in the seed bed provide niches of suitable temperature and moisture for seedling emergence (Doust et al., 2006; Elmarsdottir et al., 2003; Winkel et al., 1991). A heterogeneous soil surface can provide a variety of safe sites for seed lodgement and seedling establishment (Harper et al., 1965) with buried seeds out performing surface sown for some species (Grant et al., 1996). Soil heterogeneity can be increased by tillage, and soil raking has been shown to increase seedling emergence (Turner et al., 2006), possibly through increasing moisture penetration.

Timing of seed sowing, particularly in arid regions, can profoundly influence seedling emergence (Carrick and Krüger, 2007; Turner et al., 2006; Ward et al., 1996). In Mediterranean southwest Western Australia, a region adjacent to the study sites, emergence of *Banksia* woodland seedlings from seeds broadcast in May (autumn) was greater than seeds broadcast in July (winter) (Turner et al., 2006).

Consideration of the reconstructed soil environment prior to restoration planting is essential to optimise plant growth and survival (Rokich, 1999). Reinstated soils often exhibit altered physical and chemical characteristics, and moisture penetration and retention capabilities. Removal of upper layers of soil and compaction by heavy machinery during soil removal can result in a substrate that is chemically and biotically altered and potentially hostile to plant growth (Ashby, 1997; Enright and Lamont, 1992; Rokich et al., 2001). Compaction in restoration sites is commonly alleviated by deep ripping (Rokich et al., 2001; Szota et al., 2007;

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Ward et al., 1996) which increases plant growth (Ashby, 1997) and improves root architecture (Rokich et al., 2001).

As soil depth increases, organic matter (Williamson and Neilsen, 2003) and organic carbon (Schwenke et al., 2000) decrease, so disturbances that remove surface leaf litter and part or all of the topsoil can be detrimental to seedling growth. The removal of topsoil can, in part, be off-set by nitrogen and phosphorus amendments (Williamson and Neilsen, 2003) to counteract low nutrient availability (Close et al., 2005).

An additional limitation to seedling survival is water availability, particularly in the arid zone, where rainfall is low and seasonally variable. Compacted soils compound this limitation by restricting seedling root development, leading to dependency on surface soil moisture (Enright and Lamont, 1992). Moisture retaining gels (e.g. hydrogel or polymer gel) may provide supplemental moisture to plants when water is limited. For instance, hydrogel increased survival and growth of *Pinus halepensis* seedlings under drought conditions (Hüttermann et al., 1999). However, not all experimental uses of hygroscopic gels have produced such positive results, particularly those in field conditions (Clemente et al., 2004; Paschke et al., 2000). One approach to improve moisture balance in restored plants is to decrease the transpirational area by pruning to increase the root:shoot ratio and improve growth (Close et al., 2005). The effect of shoot pruning is commonly used in forestry, particularly in temperate areas; however the effect of shoot-pruning on plants in arid regions is yet to be tested.

The sites for this study were located within the Shark Bay World Heritage Area, in the Western Australian arid zone. Over the last 20 years, vegetation has been cleared and soil excavated for development of a large solar salt facility. These “borrow pits” remain devoid of vegetation, highlighting a need for restoration to minimise erosion and re-instate biodiversity values. Since the sites lack salvageable topsoil comprising a native soil seed bank, experiments were undertaken to evaluate the restoration potential of broadcast seed and greenstock.

This study aimed to understand how different soil amendments affect seedling recruitment and survival in restoration sites in arid Western Australia and to understand seasonal differences in seedling recruitment. For broadcast seeding, the effects of soil ripping and raking of seeds into the soil on seedling emergence were investigated over two years and in two seasons. For greenstock planting, we investigated methods to improve survival including 1) soil ripping prior to planting, 2) shoot pruning prior to planting, 3) application of slow-release fertiliser at planting, and 4) application of hygroscopic gel at planting.

2. Methods

2.1. Site description and preparation

The study sites were located at Shark Bay Resources (SBR), a solar salt facility in operation since 1965 on the Edel Peninsula within the Shark Bay World Heritage Area in Western Australia. The surface geology comprises Late Pleistocene Tamala Limestone overlain by reddish-brown calcareous sands (DEP, 2001) and the vegetation surrounding the experimental area is a low shrubland (Mattiske, 1996). The facility consists of ponds surrounded by roads and bunds, constructed using soil material extracted from pits, termed ‘borrow pits’ that require ecological restoration.

Three borrow pits were chosen for experiments on seed broadcasting and greenstock planting (pits P (26°09′29.1″ 113°23′56.0″; elevation 10 m at the base of the pit), Q (26°10′15.0″ 113°23′52.3″; elevation 8 m) and R (26°10′37.0″ 113°23′58.4″; elevation 19 m)). Experimental pits were chosen on the basis of three criteria: greater than 1 ha in area; not recently subjected to restoration works; and accessible for machinery.

In each of the three pits, a 40 m × 25 m area was marked out and enclosed by a 0.8 m high fence to discourage herbivory by kangaroos and introduced rabbits. A grader ripped half of the area (20 m × 25 m) with four 50–70 mm wide tines in April 2005. Seeds were broadcast in the ripped and non-ripped areas of pits P, Q and R in April and June 2005.

The areas that were ripped in April 2005 were ripped again in May 2006 (excluding the areas in which seeds were broadcast in 2005) and seeds were broadcast in new plots in the ripped and non-ripped areas of pits P, Q and R. Greenstock was planted in July 2006 in the ripped and non-ripped areas of pits Q and R, and the ripped area of pit P; however they were not planted in the non-ripped area of pit P as the soil was impenetrable to the depth of the root ball.

Three species were chosen for seed broadcasting: *Acacia tetragonophylla* F. Muell. (Fabaceae), *Atriplex bunburyana* F. Muell. (Chenopodiaceae) and *Solanum orbiculatum* Poir. (Solanaceae) and two of those species (*A. tetragonophylla* and *A. bunburyana*), were chosen for greenstock planting based on dominance in the surrounding vegetation, ease of propagation, and seed availability.

Daily rainfall for the study period (1 January 2005 to 31 March 2008) was monitored by SBR. Temperature of the top 1 cm of soil was monitored hourly from 1 January 2007 to 31 December 2007 using Tinytag Plus 2 data loggers (Gemini Data Loggers (UK) Ltd) placed in natural vegetation adjacent to pit P. The logger was placed on the soil surface, with the probe inserted in the top 1 cm of the soil.

2.2. Seed broadcasting

Seeds were collected from plants in the natural vegetation in September 2004 and November 2005 (and broadcast in 2005 and 2006 respectively). Seeds were cleaned, pre-treated according to Commander et al. (2009) and air-dried (*ca.* 22 °C, 50% RH), prior to broadcasting.

The effects of soil ripping and raking seeds into soil were tested individually and in combination: 1) no rip, no rake (control), 2) rip only, 3) rake only, and 4) rip + rake; in two successive years.

For each treatment, one hundred seeds of each species were evenly broadcast by hand in three replicate plots of 2 m × 2 m (with a 1 m buffer zone between each plot) in pits P, Q and R on 29 April (autumn) 2005, 28 June (winter) 2005 and 10 May (autumn) 2006. Plots containing treatments 1 and 3 were set up in the 20 m × 25 m area that was left non-ripped. Plots containing treatments 2 and 4 were set up in the 20 m × 25 m area that was ripped and these plots were set up over the rip-lines and the areas between rip-lines. Plots containing treatments 3 and 4 were raked with a garden rake, after seeds were broadcast, to incorporate the seeds into the top 2–5 cm of the soil.

Final seedling emergence data for seeds sown on 29 April and 28 June 2005 were collected on 13 November (spring) 2005. Data for seeds sown on 10 May 2006 were collected on 29 October (spring) 2006.

2.3. Greenstock

Seedlings were grown at a commercial production nursery in Geraldton, Western Australia for five months. Transplanted greenstock was subjected to four treatments: no treatment (control), application of slow-release fertiliser, shoot-pruning and application of a hygroscopic gel.

For the fertiliser treatments, one teaspoon (4.4 g) of Osmocote® Native Gardens fertiliser (a slow-release fertiliser commonly used for Australian plants; N: 17%, P: 1.6%, K: 8.7%) was applied after planting into a slit in the soil approximately 10 cm from each seedling. For the shoot-pruning treatment, seedlings were pruned to half their initial size using secateurs just prior to planting. One teaspoon of the hygroscopic gel (Rainsaver water storing crystals, Hortex Australia Pty Ltd.) was applied in a similar way to the slow-release fertiliser.

In July (winter) 2006, three replicates of 20 seedlings were planted using Pottiputki tree planters in the ripped areas of pits P, Q and R and non-ripped areas of pits Q and R. There was one row per treatment, and *A. tetragonophylla* and *A. bunburyana* were planted alternately in the row. In the ripped areas, seedlings were planted in rows along the rip lines. Each replicate was implemented in a block design. Seedling survival was assessed on 29 October (spring) 2006, 1 May (autumn) 2007, 30 October (spring) 2007 and 16 April (autumn) 2008. Seedlings were considered alive if they had living tissue, that is, green leaves and/or stems exhibiting evidence of being green with moist tissues and some bud sprout capacity.

2.4. Soil properties

Soil properties were measured at each of nine sites: ripped and non-ripped areas of pits P, Q and R (where seeds were broadcast and seedings planted); and natural vegetation adjacent to (<50 m from) the edge of the pits.

Soil was collected in May (autumn) 2007 by sampling the top 5 cm of soil from a 20 cm × 20 cm area. Three replicates, each made up of five bulked samples, were collected at each site. The soil was analysed by CSBP Limited (Cumming Smith British Petroleum, Bibra Lake, Western Australia) for electrical conductivity, pH (determined using $CaCl_2$ or H_2O), nitrate, phosphorus, sulphur, organic carbon, iron and potassium.

Volumetric soil moisture and soil impedance were measured in May (autumn) 2007, October (spring) 2007 and April (autumn) 2008. Volumetric soil moisture was measured using a MP406 Moisture probe with a MPM 160 Moisture Probe Meter (ICT International Pty Ltd). Ten readings were taken at each of the sites. Soil impedance was measured using a CP 20 Cone Penetrometer (Rimik). The penetrometer was inserted into the soil and readings were taken every 20 mm up to a maximum of 600 mm, or until it could not be inserted into the soil any further thereby measuring the force needed to penetrate the soil. Ten replicate insertions were performed at each of the sites.

2.5. Statistics

Seedling emergence and greenstock survival data were analysed as a split-plot design using binomial generalised mixed effects models (GLMM). Binomial generalised linear models based on raw numbers provide a more theoretically sound approach to analysing proportion data such as emergence and survival than traditional techniques based on conversion to percentages and mixed effects models provide an efficient and powerful means of dealing with complex nested designs, such as split-plot (Crawley, 2007). Analysis was carried out using the lme4 package (Bates and Maechler, 2009) in the R software environment (R Development Core Team, 2009). Factors considered for seedling emergence were time of broadcasting (autumn 2005, winter 2005, autumn 2006), pit (P,Q,R), species, rip (±) and rake (±). Following the split-plot design, rake nested within rip nested within pit was considered to be a random effect. Factors considered for greenstock survival were: time of assessment (spring 2006, autumn 2007, spring 2007, autumn 2008), pit (P,Q,R), rip (±) and treatment (control, fertiliser, shoot-prune, hydroscopic gel). Following the split-plot design, treatment nested within rip nested within pit was considered to be a random effect. The full model for both greenstock survival and seedling emergence was calculated; this included all main factors and interactions. Since higher-order interactions with species were found to be significant, separate models were then fitted for each species, including all main effects and second-order interactions for remaining terms. This full model for each species was then refined using stepwise elimination of explanatory factors and interactions in the standard procedure, where each term is tested in turn and terms are dropped from the model when a chi-squared test indicates that the reduction in deviance explained by dropping the term would not be significant at $P < 0.05$ (Crawley, 2007). When terms were significant they were retained and the significant *p*-value recorded for presentation. In the few cases where needed, means were separated with two-sample binomial tests using 95% confidence limit.

Soil data were analysed using Genstat 12th edition (VSN International). Soil moisture (%) and organic carbon (%) were arcsine-transformed prior to analysis and untransformed data are presented in the figures. A general analysis of variance (ANOVA) (factors were time (autumn 2007, spring 2007, autumn 2008), pit (P, Q, R) and site (rip, no rip, natural vegetation)) was used to detect differences in soil moisture and maximum penetration depth. Fisher's unprotected LSD (using a significance level of 0.05) was used to compare the means within each time period. EC, pH, nitrate, phosphorus, sulphur, organic carbon, iron and potassium were analysed using a 2-way ANOVA with pit (P, Q, R) and site (rip, no rip, natural vegetation) as the factors. Fisher's unprotected LSD (using a significance level of 0.05) was used to compare the means.

3. Results

3.1. Rainfall and soil temperature

Rainfall over the study period was highly variable. In 2005, annual rainfall of 300 mm was distributed over 10 months, and rainfall was highest in May and June (Fig. 1). Rainfall in 2006 and 2007 was lower than in 2005 with both years experiencing <100 mm p.a. (Fig. 1) with the rain distributed over a 10 month

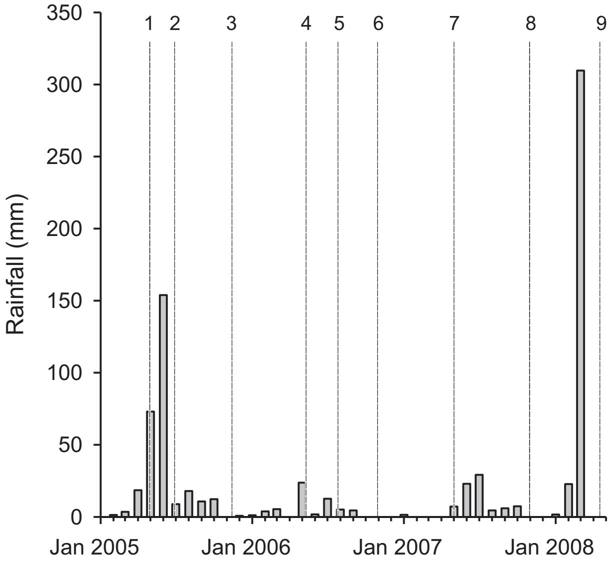

Fig. 1. Monthly rainfall (mm) at Shark Bay Resources from 1 January 2005 to 31 March 2008 Dashed lines and numbers indicate timing of experimental trials; 1: seed broadcasting April 2005, 2: seed broadcasting June 2005 3: broadcasting assessment, 4: seed broadcasting 2006, 5: greenstock planting 6: broadcasting and greenstock assessment, 7: greenstock assessment, 8: greenstock assessment, 9: greenstock assessment.

Table 1
Significance of model terms for analysis of broadcast seed data based on chi-squared test analysis of deviance. No first order terms were tested because all were present in significant second order interactions. ns: not significant at $P < 0.05$.

	Atriplex	*Acacia*	*Solanum*
Rake:pit	ns	0.0005	ns
Rake:rip	<0.0001	0.013	<0.0001
Time:pit	0.0003	<0.0001	0.0015
Time:rip	0.003	ns	<0.0001
Time:rake	ns	ns	<0.0001

period in each year. The yearly average from 2005 to 2007 (146 mm) was lower than that from 1984 to 2007 (216 mm) (SBS unpublished data, Commander, 2008). A large rainfall event in March 2008 resulted in 308 mm of rain in four days, exceeding the total rainfall for 2006 and 2007 combined (Fig. 1), and resulted in partial inundation of pit Q. Daily maximum soil temperatures in the summer months were frequently >60 °C and minimum soil temperatures were <25 °C for the duration of the year. Average maximum and minimum temperatures were 63 and 18 °C in January and 35 and 11 °C in July.

3.2. Seed broadcasting

Seedling emergence from seed broadcasting was very low, with a mean of 3% of seeds emerging across all broadcasting times, pits, species and treatments (rip and rake). Analyses revealed that for all three species, all main effects (time of broadcasting, pit, species, rip and rake) were either significant or involved in significant second order effects (Table 1). Seedling emergence was highest following broadcasting in autumn 2005 (8.3% averaged across treatments, pits and species) compared with winter 2005 (0.5%) and autumn 2006 (0.4%) (Fig. 2). This difference was particularly marked in pit P (9.2% versus 0.2% and 0%, respectively). Seedling emergence differed between the species with *A. tetragonophylla* (5.3%) exhibiting higher emergence than *A. bunburyana* (1.4%) and *S. orbiculatum* (2.5%). *A. tetragonophylla* had the highest emergence of all species at all times, while *S. orbiculatum* was lowest in Autumn 2006 and *A. bunburyana* lowest in Winter 2005. Overall, both rip and rake increased seedling emergence; 2.8-fold and 2.4-fold, respectively, although raking had no effect in Autumn 2006. The combination of rip and rake further increased emergence in some instances, for example, emergence of *A. tetragonophylla* seeds broadcast in autumn 2005 increased from 12.8% (rake) and 14.2% (rip) to 27.4% (combination) (Fig. 2).

3.3. Greenstock

Seedling survival two years after planting ranged from 0 to 92%, with *A. bunburyana* out performing *A. tetragonophylla*. Most of the *A. tetragonophylla* seedlings died within three months of planting (Fig. 3) and by spring 2006 there was <17% *A. tetragonophylla* survival in all areas, except the ripped area of pit R (17–37% survival). Despite the overall low survival, analyses showed that ripping was significant as a main effect, while the other factors were significant in second order interactions (Table 2). With respect to planting time, survival decreased after the first spring of 2006, but not subsequently; and with respect to pit, survival in pit Q was lower than pit P or pit R. Rip increased survival whilst fertiliser, shoot-pruning, and hygroscopic gel all appeared to not influence, or decrease, survival. By autumn 2008, survival was <13%.

Average survival of *A. bunburyana* seedlings at the conclusion of the study period, autumn 2008, was 42%, and the treatment with the highest survival (92%) at that time was pit R + rip + fertiliser (Figs. 4 and 5). Analysis of seedling survival of *A. bunburyana* showed that ripping and treatment were significant as main effects, while the other factors (time and pit) were significant in second order interactions (Table 2). Rip increased survival of *A. bunburyana* ($P < 0.05$) at all times (Fig. 4a). In general, survival in pit Q was lower than in pit P or pit R. Fertiliser reduced survival in pits P and Q, but increased it in pit R. Shoot pruning decreased survival in all pits. Hygroscopic gel did not influence survival in any pits.

Even though it was not possible to test the interaction between rip and pit, due to the lack of replicate ripped and non-ripped areas within each pit in the split-plot design, a binomial test showed lower survival in the non-ripped area of pit Q compared to the non-ripped area of pit R ($P < 0.001$). Seedling survival decreased over time and in both treatments (± rip), with mortality generally occurring before the first survival counts were taken. The next highest mortality occurred in the second summer in the ripped treatments, but in the first summer for the non-ripped treatments (Fig. 4a). The pattern of seedling deaths also depended on the pit (Fig. 4b). In pit R, survival decreased over the first summer (between spring 2006 and autumn 2007) ($P < 0.05$), then remained stable for the remainder of the study period (Fig. 5c and d). In pit Q, survival was the same before and after the first summer, but decreased over the second summer ($P < 0.05$) (Fig. 5a and b). In pit

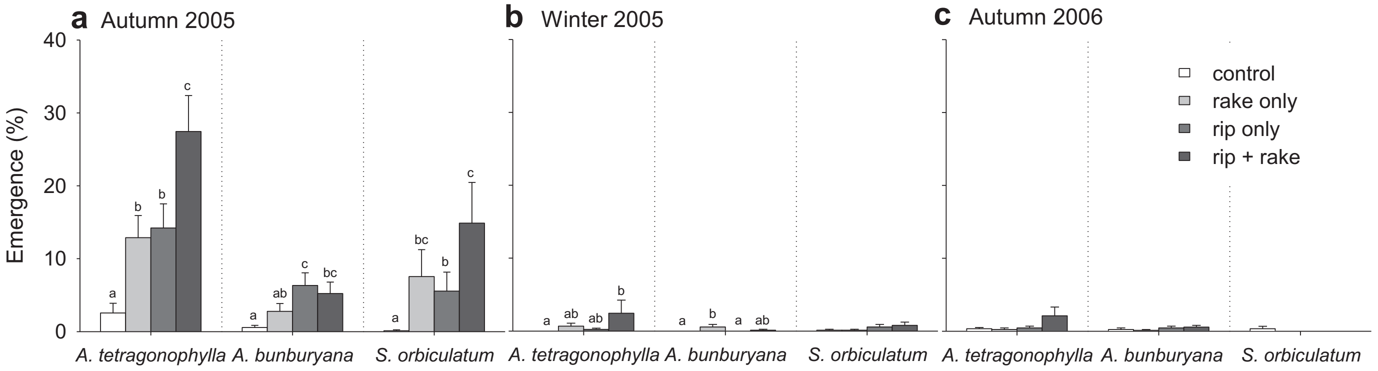

Fig. 2. Final emergence (%) of *Acacia tetragonophylla, Atriplex bunburyana* and *Solanum orbiculatum* seeds sown in **a**, autumn 2005. **b**, winter 2005. **c**, autumn 2006 and subjected to one of four treatments; control, rake only, rip only, rip + rake. 100 seeds were sown in each treatment. Values are averages across the three borrow pits. Bars indicate standard error. Letters indicate significant ($P < 0.05$) differences between the means of each species at each month.

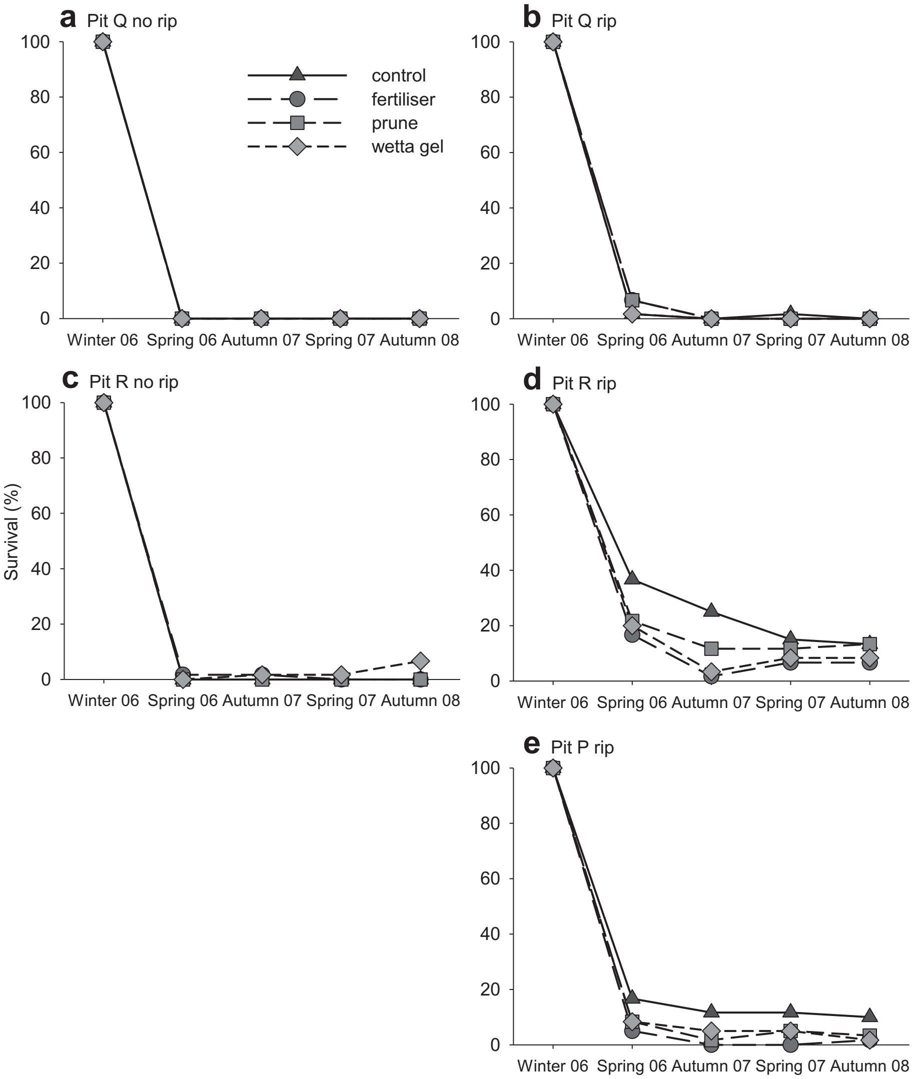

Fig. 3. Survival (%) of *Acacia tetragonophylla* seedlings in non-ripped (**a**,**c**) and ripped (**b**,**d**,**e**) areas of pits Q (**a**,**b**), R (**c**,**d**) and P (**e**) from planting in winter 2006 to autumn 2008.

P, almost all of the seedling deaths occurred prior to spring 2006, with survival remaining stable over the first and second summers (Fig. 5e).

3.4. Soil properties

Soil moisture was significantly different between the pits ($P < 0.001$), sites (rip, no rip and natural vegetation) ($P < 0.001$) and season ($P < 0.001$) (Fig. 6). Soil moisture was higher in pit Q than pit P, which in turn was higher than pit R ($P < 0.05$). Within pits P and Q, soil moisture was higher than in the natural vegetation ($P < 0.05$). Soil moisture was higher in autumn 2007 compared with autumn 2008 and spring 2007 ($P < 0.05$).

Electrical conductivity was significantly different between the pits and the sites ($P < 0.05$) (Table 3). The most notable difference was that the areas within pit Q (rip and no rip) had EC values 100 times higher than within pit R and the natural vegetation adjacent to all pits. EC values in pit P fell between those in pit Q and pit R.

Nutrient content of the soils differed between pits. The phosphorus content was lower within the pits compared to the natural vegetation adjacent to each pit ($P < 0.05$) (Table 4). Organic carbon was lower in the ripped area of each pit compared to the natural vegetation. Nitrate, potassium and sulphur were higher within pit Q compared with all other sites ($P < 0.05$). Iron was higher in the non-ripped area of pit Q and the natural vegetation compared with other sites ($P < 0.05$). Overall, when comparing the pits to the natural vegetation, pit R was the most similar to the natural vegetation with no difference recorded for four of the six nutrients, whilst pit Q was the most dissimilar with differences recorded for all six nutrients. When comparing the ripped to the non-ripped soils, differences were negligible.

Table 2
Significance of model terms for analysis of greenstock data based on chi-squared test analysis of deviance. Some first order terms (indicated with na) were not tested because they were present in significant second order interactions. ns: not significant at $P < 0.05$.

	Atriplex	*Acacia*
Time	na	na
Treatment	na	0.040
Rip	0.0007	<0.0001
Pit	na	na
Time:rip	ns	ns
Time:pit	<0.0001	0.037
Treatment:pit	0.006	ns

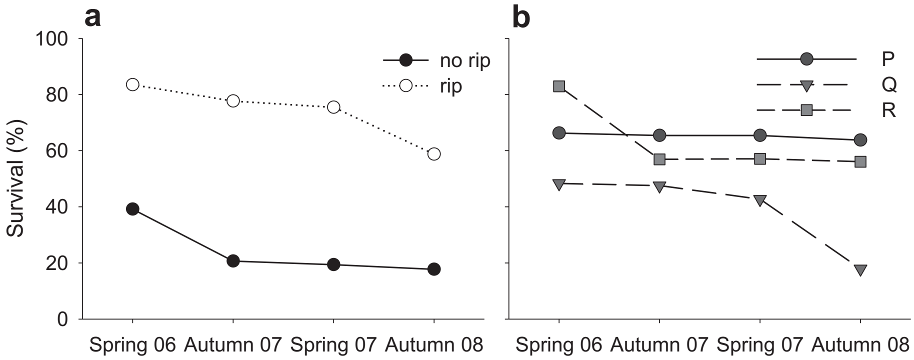

Fig. 4. Seedling survival of *Atriplex bunburyana* from Spring 2006 to Autumn 2008 averaged across **a**, the rip (plots P,Q and R) and no rip (plots Q and R only) treatments. **b**, the three pits, P (rip only), Q and R (rip and no rip).

Soil penetration depth was affected by pit, site and season ($P < 0.05$). Penetration depth was greater in pits Q and R compared with pit P ($P < 0.05$). The highest maximum penetration depth was recorded in the natural vegetation, followed by the ripped areas, with the non-ripped areas having the lowest depth of penetration ($P < 0.05$) (Figs. 7 and 8). Soil impedance in the top 120 mm of the soil profile in the ripped areas of pits Q and R was similar to the adjacent natural vegetation, whereas the non-ripped areas had higher soil impedance. Beyond 120 mm, there was generally no penetration in the non-ripped areas, and if there was, soil

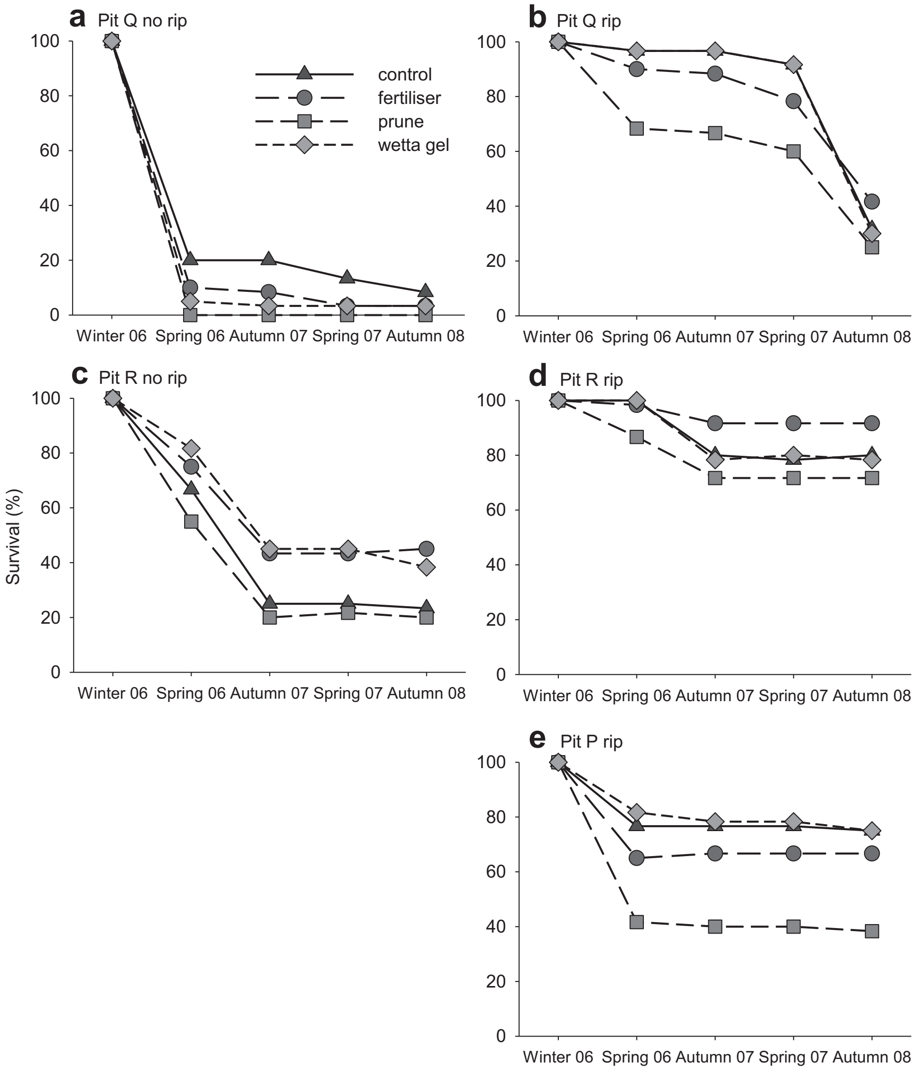

Fig. 5. Survival (%) of *Atriplex bunburyana* seedlings in non-ripped (**a**,**c**) and ripped (**b**, **d**, **e**) areas of pits Q (**a**,**b**), R (**c**,**d**) and P (**e**) from planting in winter 2006 to autumn 2008.

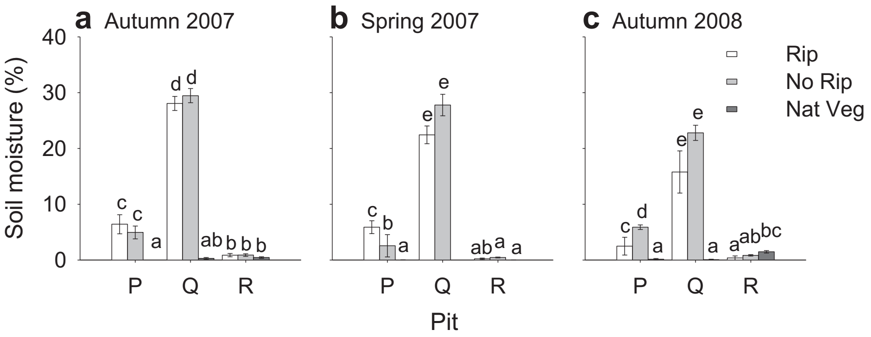

Fig. 6. Volumetric soil moisture in **a**. autumn 2007. **b**, spring 2007. **c**, autumn 2008 in the ripped and non-ripped areas of borrow pits Q and R and the surrounding natural vegetation. Bars indicate standard error. Letters indicate significant ($P < 0.05$) differences between the means within each graph.

Table 3
Mean (±SE) electrical conductivity (dS/m) and pH in the top 5 cm of the soil in the ripped and non-ripped areas of pits P, Q and R and the natural vegetation adjacent to the pits. Means were determined from three replicates, each made up of five bulked samples. Letters indicate significant differences ($P < 0.05$) as determined by Fisher's unprotected LSD. Significance of pit:site interaction based on ANOVA is indicated for each soil parameter.

Pit	Site	EC	pH ($CaCl_2$)	pH (H_2O)
P	Rip	2.3 ± 0.4 b	7.8 ± 0.0 a	8.6 ± 0.1 a
	No rip	3.2 ± 0.7 c	7.9 ± 0.0 a	8.7 ± 0.0 ab
	Nat veg	0.2 ± 0.0 a	7.8 ± 0.0 a	8.8 ± 0.1 abc
Q	Rip	10.00 ± 0.00 d	8.1 ± 0.1 b	8.7 ± 0.0 a
	No rip	10.00 ± 0.00 d	8.4 ± 0.1 c	9.0 ± 0.1 bcd
	Nat veg	0.14 ± 0.01 a	7.8 ± 0.1 a	9.0 ± 0.1 cd
R	Rip	0.09 ± 0.00 a	7.8 ± 0.1 a	9.2 ± 0.1 de
	No rip	0.10 ± 0.00 a	7.9 ± 0.0 a	9.3 ± 0.1 e
	Nat veg	0.11 ± 0.01 a	7.8 ± 0.1 a	9.0 ± 0.1 cd
	Pit:site	<0.001	<0.001	0.046

impedance was higher than the ripped sites (Fig. 7). Penetration depth was greater in autumn 2008 compared with spring 2007 and autumn 2007 ($P < 0.05$).

4. Discussion

Our study highlights the challenges of re-instating vegetation in altered landscapes in arid zone environments. We achieved very low (3%) emergence from broadcast seeds even with prior dormancy-breaking treatment, and soil amendments only marginally improved emergence. Survival of planted seedlings ranged from 0 to 92%, and although soil ripping improved survival, there were differences between species and planting sites and limited benefit from fertiliser and hydroscopic gel to early establishment.

Manipulating the soil environment using soil ripping was the most beneficial intervention, given that it increased both seedling emergence and greenstock survival. Soil ripping, and soil raking, improved seedling emergence for the sowing event that received the greatest rainfall (autumn 2005), and to a far lesser extent the winter 2005 sowing event. But no improvement was noted for the autumn 2006 sowing. Soil ripping may create microsites that are important for seed germination, seedling emergence, and ultimately seedling establishment. For example, seeds sown in furrows (or rip-lines) have higher seedling establishment compared with those sown on undisturbed soil (Doust et al., 2006) and seeds sown in cracks in the soil surface have greater seedling emergence compared with those sown on bare soil (Winkel et al., 1991). Turner et al. (2006) found raking increased emergence of eight out of nine native species and Doust et al. (2006) found buried seeds of rainforest species had higher establishment compared with seeds sown on the soil surface. These microsites may provide shelter for seedlings (Elmarsdottir et al., 2003) by decreasing wind exposure, which may decrease wind erosion and soil and seedling desiccation, compared with the smooth soil surface of the control plots. Wind erosion was shown to displace, on average, 67% of broadcast seeds from post-mined restoration sites that were highly exposed to wind (Ord, 2007). For these seeds, displacement was greatest when seeds were placed on the crests of rip lines parallel to the wind direction, and significantly reduced when seeds were placed on stippled sand or in the furrows of the rip lines (Ord, 2007).

In all pits, the soil was highly compacted and ripping partly alleviated this compaction (illustrated by lower soil impedance and greater penetration depth) and increased survival of planted seedlings; seedling survival of *A. bunburyana* in the ripped areas was, on average, three times greater than in the non-ripped areas. In other ecosystems, soil ripping increased seedling survival of

Table 4
Mean (±SE) nutrient content in the top 5 cm of the soil in the ripped and non-ripped areas of pits P, Q and R and the natural vegetation adjacent to the pits. Means were determined from three replicates, each made up of five bulked samples. Letters indicate significant differences ($P < 0.05$) as determined by Fisher's unprotected LSD. Significance of pit:site interaction based on ANOVA is indicated for each soil parameter.

Pit	Site	Nitrate mg kg^{-1}	Phosphorus mg kg^{-1}	Sulphur mg kg^{-1}	Organic carbon %	Iron mg kg^{-1}	Potassium mg kg^{-1}
P	Rip	3.0 ± 0.6 a	2.3 ± 0.3 a	105.5 ± 34.0 a	0.3 ± 0.02 a	63 ± 9.5 ab	175 ± 8.0 b
	No rip	5.3 ± 2.3 a	2.3 ± 0.3 a	196.5 ± 70.0 a	0.3 ± 0.01 a	83 ± 17.5 bc	211 ± 41.2 b
	Nat veg	6.7 ± 1.2 a	7.7 ± 0.3 b	19.5 ± 5.4 a	0.8 ± 0.04 e	113 ± 15.0 cd	64 ± 4.7 a
Q	Rip	13.3 ± 3.0 b	4.0 ± 0.0 a	1001.7 ± 173.3 b	0.50 ± 0.04 c	55 ± 6.6 ab	478 ± 66 c
	No rip	13.3 ± 3.8 b	4.3 ± 0.3 a	1147.3 ± 34.2 b	0.69 ± 0.06 d	128 ± 2.4 d	594 ± 73 d
	Nat veg	6.3 ± 1.5 a	15.7 ± 0.7 b	13.6 ± 3.1 a	0.66 ± 0.03 d	121 ± 13.9 d	66 ± 7 a
R	Rip	1.0 ± 0.0 a	4.3 ± 0.3 a	8.2 ± 0.3 a	0.21 ± 0.01 a	32 ± 2.4 a	21 ± 2 a
	No rip	1.7 ± 0.3 a	8.7 ± 0.9 b	7.3 ± 0.5 a	0.39 ± 0.03 b	54 ± 14.5 ab	30 ± 3 a
	Nat veg	4.7 ± 0.3 a	30.3 ± 1.8 d	8.2 ± 0.7 a	0.63 ± 0.05 d	53 ± 13.6 ab	65 ± 7 a
	Pit:site	0.042	<0.001	<0.001	<0.001	ns	<0.001

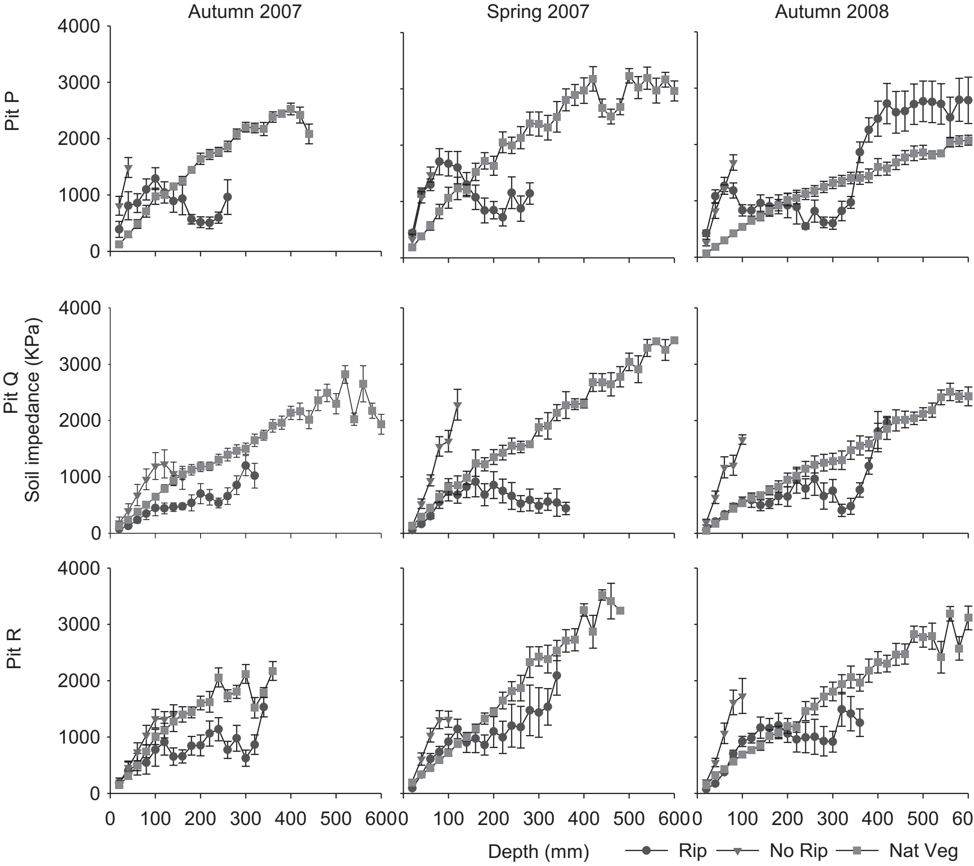

Fig. 7. Soil impedance (KPa) in autumn 2007, spring 2007 and autumn 2008 in the ripped (Rip) and non-ripped (No Rip) areas at pits Q and R, and natural vegetation (Nat veg) adjacent to the pits. Averages were only calculated when there were at least three readings at that depth. Bars indicate standard error.

Pinus echinata (Gwaze et al., 2007), *Pinus radiata* (Simcock et al., 2006) and *Acacia hemiteles* (Yates et al., 2000) and in post-mine and post-quarry restoration in Western Australia, soil ripping is a common practice (Gardner, 2001; Rokich et al., 2001; Szota et al., 2007; Ward et al., 1996). Higher seedling survival in ripped soils compared with non-ripped soils in this study can be partly attributed to the alleviation of soil impedance that would allow improved root growth and development.

Seasonal differences in seedling emergence are likely due to differences in rainfall. Higher seedling emergence was achieved from seed broadcasting in autumn 2005 (≤27%) compared with autumn 2006 (<4%) and annual rainfall was 300 mm and 58 mm, respectively. Impact of sowing time on seedling emergence has been demonstrated in studies in south and southwest Australia (Knight et al., 1998; Turner et al., 2006) with seeds sown in autumn exhibiting greater seedling emergence compared with seeds sown in winter (Turner et al., 2006).

Soil moisture levels were higher in the borrow pits compared to the adjacent natural vegetation, a similar result to that found for reconstructed soils in mined areas in southwest Australia (Rokich et al., 2001), the exception being pit R where soil moisture levels were similar to the adjacent natural vegetation. Whilst our study has highlighted the importance of rainfall for seedling emergence, the similar soil moisture levels in ripped and non-ripped soils, accompanied by dissimilar seedling survival levels, suggest that factors other than soil moisture (such as compaction) may be of

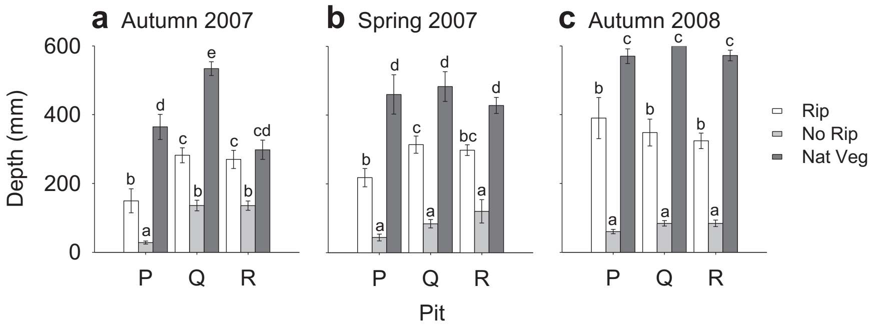

Fig. 8. Maximum penetration depth (mm) in **a**, autumn 2007. **b**, spring 2007. **c**, autumn 2008 in the ripped and non-ripped at pits P, Q and R, and natural vegetation adjacent to the pits. Bars indicate standard error. Letters indicate significant ($P < 0.05$) differences between the means within each graph.

greater importance. Moreover, whilst soil moisture differed markedly between the pits (possibly due to a difference in elevation and therefore distance to the water table), hygroscopic gel was unable to compensate for pit moisture deficits (e.g. in pit R) or improve seedling survival, again suggesting that factors other than soil moisture may play a part in seedling survival. A possible reason for the lack of benefit of hygroscopic gel in this study may be attributed to unusually low rainfall that may not have been adequate to hydrate the gel, and hence store water for the roots to access. But studies by Paschke et al. (2000) and Clemente et al. (2004) also found no effect of hygroscopic gel on survival of seedlings.

Electrical conductivity of the soil differed between the pits, apparently affecting the two species in different ways. Electrical conductivity was substantially higher in pit Q (saline) compared with the adjacent natural vegetation and pits P (slightly saline) and R (non-saline) (DAFWA, 2006). High salinity in pit Q may explain the lower survival of *A. tetragonophylla* in pit Q (0% survival after 1 year) compared to pits P and R. In addition, salinity may explain some of the differences in survival between the two species, *A. bunburyana* showed higher survival (ca. 92%) than *A. tetragonophylla* (ca. 13%) after two years. *A. bunburyana* did not seem to be adversely affected by the electrical conductivity in pit Q when the soil was not compacted, as survival in the ripped areas of pits Q and R were similar in 2007 (prior to the inundation event in 2008). However, the combination of high electrical conductivity and compaction, may have negatively affected survival as shown by the lower survival in the non-ripped soil of pit Q compared to the non-ripped soil of pit R. Growth of many plants is limited at high salt concentrations, however, saline soils can be beneficial for other plants (Barrett-Lennard et al., 2003) such as *Atriplex* spp., being halophytes, and adaptations for survival in saline environments include the ability to excrete salt from the plant via bladder-like cells on the leaf epidermis (Lambers et al., 1998). For example, growth of *Atriplex amnicola* increases by 10% when grown at 5 dS m^{-1} compared with 2.5 dS m^{-1} (Aslam et al., 1986) and growth of *A. bunburyana* is not affected by soil salinity up to 5 dS m^{-1} (Jefferson, 2001). Higher success of *A. bunburyana* compared with other species in Western Australian mine rehabilitation has been noted (Jefferson, 2004) and higher survival of *Atriplex semibaccata* (60–80%) compared with *A. hemiteles* ($<$50%) has been found in Western Australia (Yates et al., 2000). The differences in survival between pits and species in this study indicates that survival of a larger suite of species across different soil types will need to be investigated before broad-scale planting and seeding occurs.

Additional differences in soil nutrients included higher organic carbon and phosphorus in the natural vegetation compared with two or more pits, a finding similar to that of Rokich (1999). Organic carbon content is important, as it can be used as a key measure of soil formation, and is used to assess restoration success (Koch and Hobbs, 2007). Clearly, the difference between organic carbon content of the disturbed and adjacent undisturbed soils indicates that soil-creation is ongoing.

Given that this is the first restoration study to be undertaken in this ecosystem, initial results have been useful to point the direction towards further work to better understand the ecology of seedling emergence and ecophysiology of seedling health. This study has shown that soil preparation (soil raking and/or ripping) can increase seedling emergence and survival. However, this study also demonstrates the difficulty of returning vegetation, via seed and greenstock, to disturbed sites in the Shark Bay World Heritage Area. Seedling emergence from seed broadcasting was limited by rainfall, and only in the event of high rainfall (2005) was there the possibility to demonstrate soil treatments had the potential to improve seedling emergence. Species-specific responses from two plant sources highlight the difficulty in selecting the effective method of returning plants of each species and the need to assess treatment effects and survival of individual species. Indeed, more than one plant source may be necessary in this arid zone to achieve the necessary densities of plants and diversity of species. However, under low rainfall (e.g. 2006), it was clear that higher numbers of plants of both species (as a proportion of seeds) were present following greenstock planting compared with broadcast seeding. From a seed conservation perspective, greenstock planting is a better option at this site, given that the areas of disturbance are relatively small, however greenstock would not be an economically viable for restoration of large areas. Given the low rainfall during the study period, an investigation of plant sources under higher rainfall is needed to determine the relative benefits of seed broadcasting and greenstock planting to re-instate vegetation communities, from both a seed conservation and economic perspective.

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