Influence of Polymer Seed Coatings, Soil Raking, and Time of Sowing on Seedling Performance in Post-Mining Restoration

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Abstract

This study represents part of a broader investigation into novel seed broadcasting methodologies as a means to optimize rehabilitation techniques following sand mining. Specifically, the study investigated the use of polymer seed coatings, time of sowing application, and in situ raking of the topsoil to optimize seedling recruitment to site. For polymer seed coatings, an ex situ trial was undertaken to evaluate seed coating effects on seedling emergence. Results demonstrated that seed coatings did not significantly inhibit maximum emergence percentage of 10 *Banksia* woodland species (out of 11 evaluated), but coated seeds from four species were on average 2–6 days slower to emerge than noncoated seeds. Seed coatings were found to have a greater effect in situ, with more coated seeds emerging than noncoated seeds. Topsoil raking (following seed sowing) and time of sowing were found to have the greatest impact on seedling emergence, with higher emergence following topsoil raking (5- to 90-fold increase) and sowing in May (late autumn) (1.4- to 12-fold increase) rather than in July (mid-winter). The implications for mining rehabilitation are discussed, and areas for further research are considered.

Key words: *Banksia* woodland, land restoration, polymer seed coats, seed broadcasting, seed germination.

Introduction

Restoration following mining is often problematic as there are many limitations to the reestablishment of native vegetation including both biotic and abiotic factors, such as predation, competition, moisture, and temperature (Majer 1983; Bell et al. 1995; Cummings et al. 2005). One particularly challenging vegetation community to restore following major disturbance is *Banksia* woodland, a floristically rich assemblage found growing on extremely poor sands in Western Australia.

Banksia low woodland is the characteristic vegetation type along the sandplains of the Swan Coastal Plain in the southwest of Western Australia (Beard 1989). The woodland is representative of the many plant communities within the biodiverse kwongan region to the north and west of the Swan Coastal Plain (Dodd & Griffin 1989). The woodland extends from Jurien to the north (200 km from Perth), Busselton to the south (250 km south of Perth), and Dandaragan Plateau to the east (Beard 1989), and as part of the broader southwest botanical region, is the only biodiversity hotspot in Australia (Myers et al. 2000; Mittermeier et al. 2004). Significantly, this region is also the most heavily populated and impacted, with over 80% of these woodlands already cleared (Hopper & Burbidge 1989; D. Rokich, personal communication).

Regardless of the simple structure and uniform appearance, *Banksia* woodlands are floristically rich and taxonomically diverse (Dodd & Griffin 1989). The lack of floristic uniformity in species composition has lead to the division of *Banksia* woodlands into a number of floristic types. However, the defining characteristic is the small trees (usually *Banksia* spp.), 6–8 m tall, which dominate the overstorey, and the much lower well-developed sclerophyllous shrubby understorey. The tree canopy generally comprises the dominants Slender banksia (*Banksia attenuata*) and Firewood banksia (*B. menziesii*), while Fraser's sheoak (*Allocasuarina fraseriana*), Tuart (*Eucalyptus gomphocephala*), Jarrah (*E. marginata*), Coastal blackbutt (*E. todtiana*), and other *Banksia* species occur less frequently. The understorey is represented by the dominant woody families Proteaceae, Myrtaceae, Fabaceae, and Ericaceae (*sensu* Epacridaceae) and monocotyledonous perennials in the Cyperaceae and Restionaceae (Dodd & Griffin 1989). However, due to extensive clearing and habitat modification, many plant and animal species found in this

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vegetation community have declined in numbers to the point where they are now considered highly vulnerable or endangered (Hopper & Burbidge 1989; Brown et al. 1998; Specht & Specht 1999).

Unfortunately, *Banksia* woodlands continue to be cleared and degraded for urbanization, horticulture, recreation, and mining activities, without sufficient conservation practices in place. Only 20% of the original *Banksia* woodland habitat remains, making both conservation of *Banksia* woodlands and restoration of degraded woodlands critical for conservation in the region. Conversely, information on the management requirements and the restoration ecology and biology of *Banksia* woodland species is limited. To date, much of the research on restoration of *Banksia* woodlands has focused on utilizing soil seed banks to "inoculate" rehabilitation sites with seeds. It is now well documented that the *Banksia* woodland soil seed bank provides a valuable source of seed for rehabilitation of areas that have been impacted by sand mining activities (Rokich 1999; Rokich et al. 2002). Indeed, Rokich et al. (2000) demonstrated that topsoil containing seeds, removed and replaced dry during autumn (before the onset of winter rains) to a maximum thickness of 10 cm, improves seedling establishment in sites undergoing rehabilitation. Although topsoil application is the most useful, reliable, and economical source of plants, it has limitations, particularly for species whose seeds are canopy stored (bradysporous) and only released following fire or other major disturbances. Other species such as legumes within the Fabaceae can also be under-represented within topsoil return sites for reasons that are poorly understood. As a result, these species must be returned to post-mining sites as either broadcast seed or greenstock (seedlings).

Seed broadcasting in post-mined areas results in significantly higher seedling recruitment than in areas where no seeds are broadcast (Koch & Ward 1994), but often the proportion of broadcast seeds that germinate is very low. Rokich et al. (2000) reported that just 7% of broadcast seeds delivered to site recruited into seedlings. The remaining 93% of seeds did not establish seedlings within the study area. Similar cases involving aerial seeding also failed to show positive results (Greipsson & El-Mayas 1999). It is assumed that the low efficiency rates of broadcast seed in post-mining rehabilitation is related to a number of factors, of which seed predation and wind and water erosion are likely to be the most important.

Seed coating, or seed pelleting, is a process whereby seeds are covered with filler materials and binders that facilitate mechanical dispersal. The coating or pelleting also allows the incorporation of various chemicals such as pesticides, fungicides, and growth-promoting substances that aid in seed germination and enhance early seedling performance (Venning 1988). Seed coating or pelleting produces larger, rounder, smoother, and uniformly sized seeds that are suited to mechanical seed sowing equipment. Coatings have also been reported to decrease the risk of imbibitional damage during germination, as imbibition can be regulated to provide increased or decreased moisture in line with the optimal amount required for germination (Anonymous, 2004*a*). Coatings can be customized to allow "melting" or "splitting" for light-sensitive seeds, or to facilitate fast oxygen uptake (Anonymous, 2004*a*). As a result, seed coatings are widely used in horticulture to allow for precision seed sowing and optimal seedling emergence. Surprisingly, seed coatings are yet to be introduced for broad-scale rehabilitation.

Other factors such as topsoil cultivation (following seed sowing) and time of seed sowing have also demonstrated an effect on seedling recruitment rates (Brofas & Karetsos 2002; Mason & Hocking 2002); yet, their impact on seedling recruitment in *Banksia* woodland rehabilitation sites following seed broadcasting has not been quantified.

This study aimed to develop seed-based rehabilitation techniques, particularly following sand mining within *Banksia* woodland, through investigation of recent developments in seed broadcasting technology. Specifically, the aims were to (1) determine the effect of seed coatings on the seedling recruitment of native *Banksia* woodland species, under ex situ and in situ conditions; (2) determine the effect of topsoil raking following seed broadcasting on seedling recruitment; and (3) measure the effect that season of seed sowing has on seedling recruitment.

Methods

Location and Climate of In Situ Studies

The study site was the Banjup sand extraction quarry, 20 km south of Perth, Western Australia, owned and operated by Rocla Quarry Products Pty. Ltd. The 100-ha site extends over three leaseholds on the Bassendean dune system and supports *Banksia* woodland.

The site experiences a Mediterranean climate, characterized by hot dry summers (December–February), with an average diurnal temperature range of 15–32°C, followed by mild moist winters (June–August), with an average diurnal temperature range of 8–19°C (Anonymous, 2004*b*). Almost 900 mm of precipitation is received annually, with over half falling during winter (June–August) (Milewski & Davidge 1981).

Two rehabilitation sites within the quarry were used for the in situ trials. Both sites were located approximately 300 m apart and were extremely similar, consisting of the same soil type (Bassendean sands), topography, orientation, and vegetation assemblage. The extant vegetation consisted of very sparse, low-growing native species that had recruited in the year of rehabilitation operations (1998/1999). Given the limited species richness and low plant biomass following rehabilitation, these sites were deemed to be suitable for large-scale in situ seed broadcasting trials.

Seed Material and Treatment

Eleven native *Banksia* woodland species were evaluated (Table 1), all of which are routinely used during rehabilitation

Table 1. Eleven *Banksia* woodland species used in this study, showing the family, seed syndrome, life form, seed dormancy classification, and the method used for overcoming seed dormancy.

Species	*Group*	*Family*	*Seed Syndrome*	*Life Form*	*Seed Dormancy Type (If Applicable)*	*Seed Pre-Treatment (If Applicable)*
Allocasuarina fraseriana	One	Casuarinaceae	Bradysporous	Tree up to 15 m tall	Nondormant	Not required
Banksia menziesii	One	Proteaceae	Bradysporous	Tree up to 10 m tall	Nondormant	Not required
Bossiaea eriocarpa	One	Papilionaceae	Geosporous	Shrub, 0.6 m tall	Physical dormancy	Hot water treatment for 1 min
Gompholobium tomentosum	One	Papilionaceae	Geosporous	Shrub, 0.3–1 m tall	Physical dormancy	Hot water treatment for 1 min
Melaleuca scabra	One	Myrtaceae	Bradysporous	Shrub up to 1 m tall	Nondormant	Not required
Acacia pulchella	Two	Mimosaceae	Geosporous	Shrub, 0.5–2 m tall	Physical dormancy	Hot water treatment for 1 min
Anigozanthos manglesii	Two	Haemodoraceae	Geosporous	Herbaceous perennial up to 1.3 m tall	Physiological dormancy	100°C for 3 hr
Banksia attenuata	Two	Proteaceae	Bradysporous	Tree up to 10 m tall	Nondormant	Not required
Nemcia capitata	Two	Papilionaceae	Geosporous	Shrub, 0.2–0.8 m tall	Physical dormancy	Hot water treatment for 1 min
Kunzea ericifolia	Two	Myrtaceae	Bradysporous	Erect shrub up to 3 m tall	Nondormant	Not required
Regelia ciliata	Two	Myrtaceae	Bradysporous	Erect shrub up to 2 m tall	Unknown	Aerosol smoke for 1 hr

work at sand quarries operated by Rocla Quarry Products Pty Ltd. The species were selected to represent dominant local species, which possessed varying seed syndromes (Table 1), seed sizes (Table 2), seed appendages (Table 2), and life forms (Table 1). Species were also readily germinable, with known seed dormancy mechanisms (Table 1).

All seeds, purchased from local commercial seed suppliers, were collected in 2003/2004. Seed length and weight were determined for all species, both with and without seed coating. This was undertaken on three replicates of 20 seeds.

All 11 species were coated in a process known as pelleting by the commercial seed coating company Seed Solutions. This technology is nonpublished and its exact composition and application are commercially confidential, though individual seeds appear to be bulked up with layers of surrounding inert fillers and binders and then covered by a layer of polymer coating. The coating used in this study is a commercially available product that is commonly used for horticultural species.

Ex Situ Seedling Emergence Trial

An ex situ seedling emergence trial was undertaken under standard germination conditions to evaluate the effect of coating on seedling emergence.

For coated and noncoated seeds, four replicates of 25 seeds for each species (four replicates of 10 seeds for each *Banksia* spp. given limited seed numbers) were sown in plastic punnets containing soil mixture consisting of four parts composted jarrah sawdust to two parts nursery sand to one part coarse river sand. To adjust the pH of the soil mix to 6 (optimal soil pH for germination and growth of most southwest Australian native species), 1 kg of lime and 800 g of dolomite were added per 1 m^3 of soil. Prior to use, the soil mixture and punnets were steam-pasteurized for one hour at 60–70°C to kill any pests and diseases present.

Where necessary, pre-treatments were applied to overcome dormancy (Table 1) for all coated (prior to coating) and noncoated seeds. All seeds were sown in the soil at a uniform depth, with small seeds (<2 mm in length) covered with approximately 2 mm of soil and larger seeds (>3 mm) were covered with 5–7 mm of sieved soil following sowing. Seeds were then thoroughly watered and incubated at 18°C (±2°C) and illuminated by standard fluorescent globes (36 W) running on a 12-hour timer. Thereafter, watering was undertaken as necessary (when the soil surface appeared relatively dry). Punnets were monitored daily, with the number of new seedlings recorded every second day for 50 days to provide cumulative emergence, maximum emergence, and a germination rate index (GRI) calculated from the formula

$$\mathrm{GRI}(\%\mathrm{d}^{-1}) = \sum[(\mathrm{G}_i - G_{i-1})/i],$$

where i is the germination count day, G_i the percentage of seeds germinated at time i, and G_{i-1} the percentage of seeds germinated the previous count day (Maguire 1962).

Table 2. Description of all 11 study species showing the average weight (mg ± SE), average length (mm ± SE), whether arils are present, seed viability (% viability ± SE), and germination index (GI ± SE) of noncoated and coated seeds.

Species	*Treatment*	*Average Weight (mg ± SE)*	*Average Length (mm ± SE)*	*Aril*	*Germination Index (± SE)*
Acacia pulchella	Noncoated	8.1 ± 0.2	3.0 ± 0.1	Present	3.47 ± 0.21[a]
	Coated	18.1 ± 0.6	4.0 ± 0.1	Absent	3.59 ± 0.30[a]
Allocasuarina fraseriana	Noncoated	5.0 ± 0.2	7.0 ± 0.2	Absent	2.34 ± 0.19[a]
	Coated	14.4 ± 0.5	7.0 ± 0.2	Absent	2.24 ± 0.32[a]
Anigozanthos manglesii	Noncoated	0.8 ± 0.1	<1	Absent	3.65 ± 0.20[a]
	Coated	4.1 ± 0.2	2.0 ± 0.1	Absent	3.88 ± 0.19[a]
Banksia attenuata	Noncoated	84.0 ± 2.8	16.0 ± 0.5	Absent	2.41 ± 0.27[a]
	Coated	164.3 ± 5.4	18.0 ± 0.5	Absent	1.89 ± 0.26[a]
Banksia menziesii	Noncoated	77.0 ± 2.5	15.0 ± 0.5	Absent	2.16 ± 0.05[a]
	Coated	172.4 ± 5.7	17.0 ± 0.5	Absent	2.50 ± 0.51[a]
Bossiaea eriocarpa	Noncoated	2.0 ± 0.1	2.0 ± 0.1	Present	2.68 ± 0.61[a]
	Coated	5.4 ± 0.2	2.0 ± 0.1	Absent	1.98 ± 0.31[a]
Gompholobium tomentosum	Noncoated	1.0 ± 0.1	2.0 ± 0.1	Present	3.98 ± 0.28[a]
	Coated	4.9 ± 0.2	2.0 ± 0.1	Absent	3.40 ± 0.14[a]
Kunzea ericifolia	Noncoated	0.16 ± 0.1	<1	Absent	1.95 ± 0.22[a]
	Coated	2.7 ± 0.1	2.0 ± 0.1	Absent	2.14 ± 0.24[a]
Melaleuca scabra	Noncoated	0.14 ± 0.1	<1	Absent	5.82 ± 0.28[a]
	Coated	1.8 ± 0.1	2.0 ± 0.1	Absent	3.22 ± 0.30[b]
Nemcia capitata	Noncoated	4.5 ± 0.2	3.0 ± 0.1	Present	4.62 ± 0.32[a]
	Coated	14.8 ± 0.4	4.0 ± 0.1	Absent	3.20 ± 0.40[b]
Regelia ciliata	Noncoated	0.98 ± 0.1	2.0 ± 0.1	Absent	3.98 ± 0.10[a]
	Coated	3.9 ± 0.2	3.0 ± 0.1	Absent	2.28 ± 0.21[b]

For the germination index, different letters denote significant differences within species ($p < 0.05$).

In Situ Broadcast Trial

The four primary treatment combinations consisted of (1) noncoated/nonraked seeds; (2) coated/nonraked seeds; (3) noncoated/raked seeds; and (4) coated/raked seeds. The four treatment combinations were sown in either May (late autumn) or July (mid winter) for a total of eight treatment combinations (Table 3). For each sowing month, two transects in each rehabilitation site were measured (therefore four in total for each site) and every 1.5 m along the transect, a quadrat was staked out. The total length of each transect was 12 m. Each rehabilitation site was approximately 100 m^2 in area, with both sites approximately 300 m apart. Transects within each site were located between 10 and 50 m from each other and were randomly scattered through each restoration site.

Each transect consisted of four experimental treatments sown for that month (either May or July), randomly assigned into quadrats, and repeated twice along that transect. This gave a total of eight replicates (along each transect) for each of the four treatments, (2 rehabilitation sites × 2 transects × 2 replicates per transect), at each sowing month (Table 3).

Seeds were broadcast into a 0.5- × 0.5-m quadrat, with a 1-m buffer zone in between quadrats. The treatments that required raking were done with a hand-cultivator to an average depth of 5–10 mm, once the seeds had been broadcast.

Eight lots of 50 seeds from each species were used for each treatment at each sowing month, exceptions being Prickly moses (*Acacia pulchella*) (25 seeds), *B. attenuata* (15 seeds), and *B. menziesii* (10 seeds). Due to limited seed numbers for both *Banksia* spp., seeds were sown only in May, and both noncoated and coated seeds were raked following sowing. To determine the total number of recruits following winter, the total number of seedlings per treatment was recorded in October (mid-spring) after

Table 3. Description of the experimental design used for the in situ experiment undertaken at Rocla's Banjup mine site.

Primary Treatment	*Secondary Treatment*	*May Sowing[a]*	*July Sowing*
Noncoated seeds	Seeds are surface sown only (nonraked)		
	Seeds are firstly surface sown then hand-cultivated (raked)[b]		
Coated seeds	Seeds are surface sown only (nonraked)		
	Seeds are firstly surface sown then hand-cultivated (raked)[b]		

The three treatments evaluated were (1) the absence or presence of polymer seed coats; (2) the absence or presence of soil cultivation following surface sowing; and (3) time of year seed broadcasting was undertaken (May or July). All species (9) apart from *B. attenuata* and *B. menziesii* were exposed to the same three treatments. The absence or presence of polymer seed coatings was only evaluated for *B. attenuata* and *B. menziesii* due to limited seed numbers.
[a] Due to limited seed numbers, both *Banksia* spp. were sown only in May.
[b] Due to limited seed numbers, both *Banksia* spp. following sowing had all eight replicates cultivated.

frequent rainfall had ceased and when the weather had entered an early summer-like pattern.

Weather Conditions

Monthly weather data recorded at Jandakot Airport (adjacent to Banjup quarry) for the duration of this study were obtained from the Australian Bureau of Meteorology (Anonymous, 2004*b*).

Statistical Analysis

Maximum emergence data and germination index for ex situ results were analyzed relative to treatment factors by analysis of variance (ANOVA). For in situ results, data were first analyzed by multiple analysis of variance (MANOVA) with three primary independent variables (absence/presence of seed coating; absence/presence of topsoil raking following sowing; and month of sowing [May or July]) and nine dependent variables ($p < 0.05$). Wilks' lambda (pooled ratio of error variances to effect variance plus error variance) was then used to measure the strength of the association. Where differences were found, an ANOVA model was used to evaluate the main effects for individual species ($p < 0.05$). Percentage values for maximum emergence were arcsine transformed prior to analysis (nontransformed data appear in all tables and figures), with additional transformations performed where data did not conform to ANOVA assumptions of normality. All data presented in tables and figures are nontransformed, with standard errors of the mean presented where appropriate.

Results

Ex Situ Seedling Emergence Trial

The mean percentage of emerging seeds for noncoated (control) seeds ranged from 54.0 for *Bossiaea eriocarpa* (±10.1%) and *Kunzea ericifolia* (±2.6%) to 87.0 ± 3.4% for *Anigozanthos manglesii*. For the coated seeds, the mean emergence percentage ranged from 43.0 ± 4.4% for *K. ericifolia* to 93.0 ± 4.4% for *A. manglesii* (Fig. 1).

Of the 11 species, all but two (*Allocasuarina fraseriana* and *A. manglesii*) demonstrated a trend of more seedlings emerging from the noncoated seeds than from the coated seeds, though only *Regelia ciliata* showed significantly lower emergence of coated seeds (51.0 ± 3.0%) compared to nonseeds (63.0 ± 1.9%) (Fig. 1).

The majority of the species started to emerge after 12 days, except for *A. fraseriana, A. manglesii, Banksia attenuata,* and *B. menzesii*. *Allocasuarina fraseriana* and *A. manglesii* began emerging after 18 days, whereas the two *Banksia* species emerged after 30 days. After 50 days, all species achieved maximum emergence. The fastest species to reach maximum emergence was *R. ciliata* (Myrtaceae), whose noncoated seeds reached maximum emergence after 30 days (Fig. 1). The slowest species to reach maximum emergence (50 days) were noncoated seeds of *A. pulchella*; noncoated and coated seeds of *B. attenuata, B. menziesii,* and *K. ericifolia*; and coated seeds of *Melaleuca scabra*.

In general, the coated and noncoated seeds emerged at similar rates, with 8 out of the 11 species showing no significant difference in the germination index results between coated and noncoated seeds (Table 2). The three exceptions were *M. scabra*, *Nemcia capitata,* and *R. ciliata*, all of which had significantly higher germination indexes for noncoated seeds compared to coated seeds (Table 2). The number of days until first seedling emergence of noncoated and coated seeds for the majority of the species was the same, with the exception of *Acacia pulchella*, *A. fraseriana*, *B. eriocarpa,* and *R. ciliata,* where the noncoated seeds began emerging 2–6 days before the coated seeds (Fig. 1).

In Situ Seed Broadcast Trial

Seed Coating. Initial MANOVA found that coating significantly improved seedling emergence under in situ conditions (Table 4). For individual species, coating improved ($p < 0.05$) the percentage of seeds emerging for two species, *Gompholobium tomentosum* and *R. ciliata* (Table 4). Four additional species (*A. fraseriana*, *A. manglesii*, *M. scabra,* and *N. capitata*) emerged at a higher rate when coated, but this was not significant (Fig. 2). When results were pooled (Fig. 3) for all species, higher numbers of coated seeds emerged compared to noncoated seeds. For example, noncoated seeds sown in May had an average of 1.2 ± 0.3%, and 11.8 ± 1.0% seedlings emerge from both raking/nonraking treatments compared to the coated seed treatments, where 3.4 ± 0.6% and 17.0 ± 2.7% seedlings were recorded, respectively (Fig. 3). Following the July sowing, noncoated seeds recorded averages of 0.1 ± 0.1% and 9.1 ± 1.0% seedlings from both raking/nonraking treatments, whereas 0.6 ± 0.5% and 10.2 ± 1.1% seedling were observed from the coated treatments (Fig. 3). However, unlike most of the other species, the noncoated *B. attenuata* and *B. menziesii* seeds recorded higher emergence percentages than the coated *Banksia* seeds, though this was not significant for either species (Fig. 4).

Topsoil Raking. MANOVA found that topsoil raking also significantly improved seedling emergence under in situ conditions (Table 4) and had a greater effect on seedling emergence than any other factor. For example, the percentage of seedlings emerging was significantly higher in raked compared to nonraked treatments for eight out of the nine species (Table 4). The exception to this was *K. ericifolia* (Table 4; Fig. 2). Topsoil raking also increased emergence when results were pooled across species (Fig. 3). For example 11.8 ± 1.0% and 17.0 ± 2.7% seedlings were observed from both raked treatments sown in May, compared to 1.2 ± 0.3% and 3.4 ± 0.6% for the

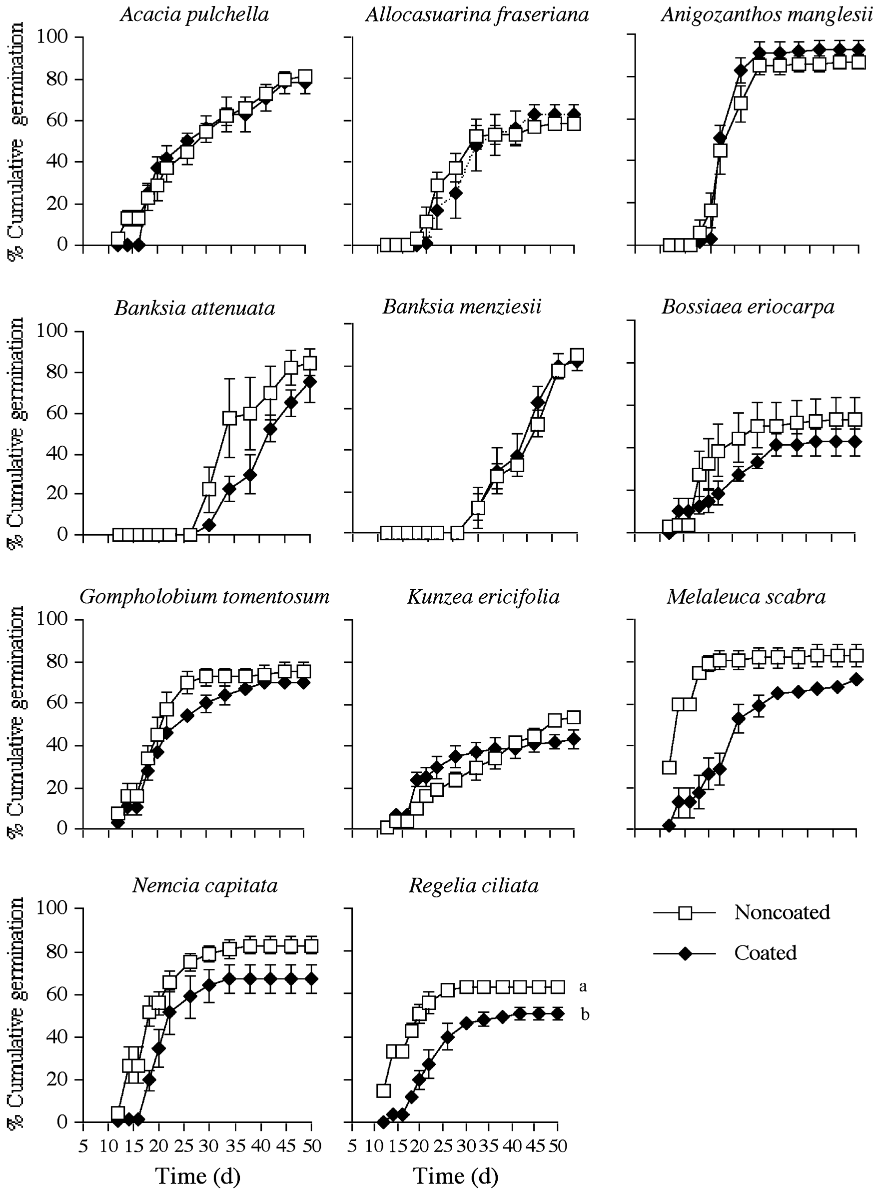

Figure 1. Average emergence rate (% ± SE, $n = 4$) over time (0–50 days) of noncoated and coated seeds of 11 *Banksia* woodland species incubated at 18 ± 2°C. Four replicates of 25 seeds each were used for all species except for *B. attenuata* and *B. menziesii,* where four replicates of 10 seeds each were used. Different letters denote significant differences between main treatments within species ($p < 0.05$).

nonraked treatments. In comparison, raked treatments sown in July were observed to have 9.1 ± 1.0% and 10.2 ± 1.1% seedlings emerge, compared to the nonraked treatments, with 0.1 ± 0.1% and 0.6 ± 0.5% seedlings recorded (Table 4; Fig. 3).

Time of Sowing. MANOVA evaluation found that time of sowing had a significant impact on seedling emergence under in situ conditions (Table 4). Overall fewer seedlings emerged from July sowings, compared to May sowings for all species except *A. pulchella* (Fig. 2); in four species, *A. fraseriana*, *A. manglesii*, *K. ericifolia,* and *R. ciliata*, this difference was significant (Table 4). When the results were pooled for all species, the noncoated/nonraked treatment and the coated/nonraked treatment recorded a 12-fold and a 6-fold decrease in emergence, respectively, when sown in July compared to May (Fig. 3). Interestingly, none of the legume species (*A. pulchella*, *B. eriocarpa*, *G. tomentosum,* and *N. capitata*) differed in terms of percentage of seeds emerging between the two sowing times.

Discussion

Restoration is part of the solution to the long-term survival of *Banksia* woodlands and related ecosystems in the

Table 4. Analysis of the responses to seed coating (noncoated or coated treatments), soil raking (sown on the soil surface and left or sown on the soil surface and lightly raked), and time of sowing (May or July) for nine *Banksia* woodland species.

Species	*Coating p Value*	*Soil Raking p Value*	*Month of Sowing p Value*	*Interaction Effects p Value*
MANOVA (with nine species as dependent variables)	**0.0002**	**<0.0001**	**<0.0001**	NS
Acacia pulchella	NS	**<0.0001**	NS	*
Allocasuarina fraseriana	NS	**<0.0001**	**<0.0001**	*
Anigozanthos manglesii	NS	**<0.0001**	**<0.0001**	*
Bossiaea eriocarpa	NS	**<0.0001**	NS	*
Gompholobium tomentosum	**0.0494**	**<0.0001**	NS	*
Kunzea ericifolia	NS	NS	**<0.0001**	*
Melaleuca scabra	NS	**<0.0001**	NS	*
Nemcia capitata	NS	**<0.0001**	NS	*
Regelia ciliata	**0.0003**	**<0.0001**	**<0.0001**	*

MANOVA was initially used (using Wilks' lambda to measure the strength of the association) to determine the presence of significant differences between the three main treatments and their interactions (if any). Where differences were found, an analysis of variance model was used to evaluate the main effects for individual species ($p < 0.05$). NS = data are not significantly different at $p < 0.05$.
* Analyses for interactions at the species level were not undertaken as MANOVA indicated that there were no interactions between the three main treatments.

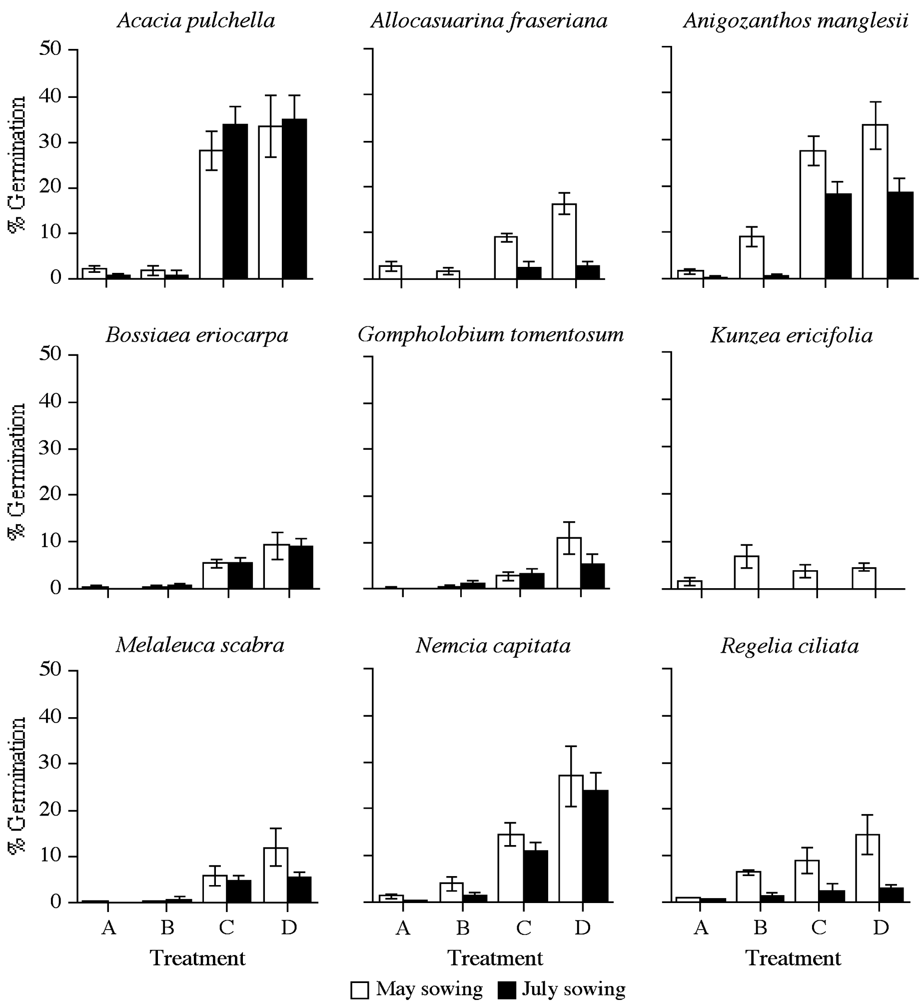

Figure 2. Average emergence (% ± SE, $n = 8$) scored at the end of the wet season (October) for the broadcast seed treatments: (A) noncoated/nonraked treatment; (B) coated/nonraked treatment; (C) noncoated/raked treatment; and (D) coated/raked treatment from broadcast seeding of nine *Banksia* woodland species on a rehabilitated mine site, sown during May and July.

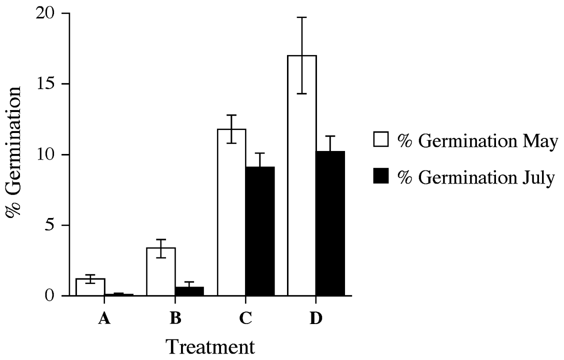

Figure 3. Average emergence (% ± SE, $n = 8$) from an in situ broadcast seeding experiment sown on a rehabilitated mine site during May and July and scored at the end of the wet season (October). The treatments evaluated were (A) noncoated/nonraked treatment; (B) coated/nonraked treatment; (C) noncoated/raked treatment; and (D) coated/raked treatment. Results are derived from pooling all nine *Banksia* woodland species together for each treatment and determining the average number of seedlings per treatment. Different letters denote significant differences between main treatments within species ($p < 0.05$).

megadiverse southwestern botanical province of Western Australia. For rehabilitation purposes, broadcast seeding will ultimately need to be a component of any large-scale restoration programs in this biodiverse region. We have demonstrated that month of sowing, soil cultivation (i.e., raking), and seed coating all substantially affect the success of seedling emergence under in situ conditions. Importantly, soil cultivation and optimizing the time of sowing are two low-cost ways to improve current recruitment rates.

Seed Coating

The most novel technique used in this study with regard to restoration was the use of coated seeds. The results presented in this study have established that polymer seed coatings may be a practical and beneficial technology as a means to improve seedling recruitment from native seeds. In the field, seed coatings increased emergence rates on average by 17–55% and the key question is whether this increase in emergence offsets the additional cost of seed coating, or whether it is cheaper to simply purchase more seeds. However, because all species used in the native plant rehabilitation industry are wild sourced, this latter solution may pose issues concerning the environmental sustainability of wild harvesting of seed.

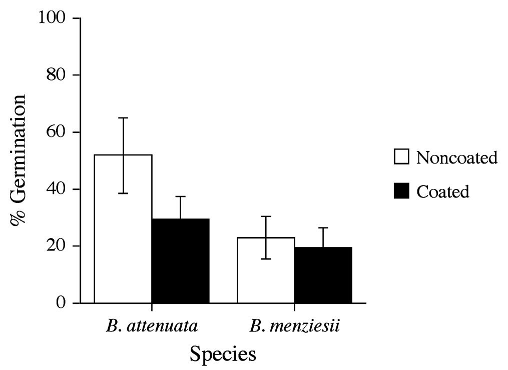

Figure 4. Average emergence (% ± SE, $n = 8$) from an in situ broadcast seeding experiment sown on a rehabilitated mine site during May for the species *B. attenuata* and *B. menziesii* and scored at the end of the wet season (October). The treatments evaluated were (A) noncoated/raked treatment and (B) coated/raked treatment.

There are very few studies in the refereed literature concerning the benefit and applicability of seed coating technologies for native seeds in the land rehabilitation/restoration or forestry/agriforestry industries. Haigh (no date) found no significant effect of seed coatings on the germination of *Eucalyptus tereticornis* seeds, though this study examined the impact of various chemicals included in the coatings, rather than the impact of the coating itself. In our study, seed coatings did not impart any major physical hindrance on maximum seedling emergence in 10 of the 11 species examined ex situ, whereas under in situ conditions, seedling emergence was overall improved. Thus, under certain conditions (such as in situ broadcasting as has been shown in this study), seed coating may assist in seed germination and emergence, a finding that has been supported by several previous authors (Haigh no date; Venning 1988; Anonymous, 2004*a*).

The higher emergence rates of coated seeds in situ could possibly be the result of the coating acting as a deterrent to seed removal by animals such as ants (Floyd 1976; Ashton 1979; Majer 1980, 1983). Alternatively, the increased weight of the coated seeds may have made them less likely to be blown or washed away. A third possibility is that the coating may have significantly reduced the amount of light the seeds received while sitting on the surface.

B. Pearce (unpublished results) found that coated seeds (of the same species reported in this study) were removed by ants at significantly lower rates compared to noncoated seeds. The possible implication from these unpublished results is that more coated seeds remained to germinate in situ due to lower rates of seed removal by ants (or other animals) compared to noncoated seeds. Although seeds removed by ants might not suffer reduced germination or survival relative to those left behind (in fact there is ample reason to expect that the seeds removed by ants could have higher survival e.g., Christian & Stanton 2004), in the context of woodland restoration, removal of seeds outside of focus sites removes the control over where seeds are germinating, which may cause problems if seeds are withdrawn from areas prone to erosion or degradation.

Alternatively, the higher percentages of coated seeds emerging in situ could also be the result of the increased weight of seeds. While a certain percentage of all seeds may be expected to blow or wash away during stormy winter weather, a larger percentage of noncoated seeds may possibly have been removed due to their lighter weight.

The other hypothesis that coated seeds sitting on the surface received significantly reduced amounts of light needs to also be considered given that many southwest Australian species are photoinhibited (Bell et al. 1995). Seed coating may therefore be another way to reduce the suppressive qualities of light for photoinhibited species that are sown on the soil surface, a finding particularly relevant to Mediterranean regions where it appears more photosuppressed species are found (Schulz & Klein 1965; Thanos et al. 1991; Bell 1993, 1994; Bell et al. 1995; McChesney et al. 1995; Rokich & Bell 1995).

Seed coatings offer the possibility of including ingredients in the coating mixture that can also regulate moisture uptake (Anonymous, 2004*a*), retain moisture around seeds for longer, or provide stress-tolerance chemicals such as acetyl salicylic acid (Senaratna et al. 2000, 2003) to the seed, thereby increasing seedling tolerance to adverse weather conditions. Other additives to the coat, such as smoke, butenolide (active chemical in smoke), and GA_3, shown to increase germination of Australian species (Bell et al. 1995; Dixon et al. 1995; Flematti et al. 2004; Turner et al. 2005) may also increase both maximum germination and the germination rate.

Topsoil Raking

While seed coating has not been extensively researched, there are more reported studies on seed broadcasting in general. In nearly all studies, seed broadcasting has been shown to yield poor results (Bellairs & Bell 1993; Koch & Ward 1994; Rokich 1999; Rokich et al. 2002). In our study, we have demonstrated that a very simple and low-cost treatment, soil cultivation following sowing, generally increases the success of broadcast seeds. These increases may be due to the covered seeds receiving subsequent protection from wind and water erosion. Post-mining sites are typically open and subjected to increased erosion and as a result, the layer of soil covering the seeds in the raked treatments may have reduced seed displacement through wind and water movement. As mentioned previously, many species from the southwest of Western Australia, the fore dune species of Australia, and the sand dune species of North America and Europe are light sensitive (Schulz & Klein 1965; Thanos et al. 1991; Bell 1993, 1994; Bell et al. 1995; McChesney et al. 1995; Rokich & Bell 1995). It is therefore not surprising that light-inhibited seed germination is a phenomenon found in species from habitats which are generally moisture limiting. Conditions including a reduction in light that are associated with soil burial and hence high moisture availability have been reported to increase germination and seedling establishment. Christian and Stanton (2004) found that increased seed burial depth resulted in increased seed survival and persistence in the soil. These authors together with Rokich et al. (2000) found the optimal depth for the highest probability of seedling emergence to be 1 cm, with increased burial depth beyond this point resulting in a negative relationship with seedling emergence. Bell et al. (1995) also reported that burial ensures a better chance of seedling survival and thought this was likely to be due to the fact that subsurface moisture availability is greater than at the surface, especially in a Mediterranean-type climate with seasonal periods of drought and stress.

In contrast to raked seeds, seeds that were broadcast without topsoil raking may also have been exposed to dispersal or predation by ants, rodents, and birds. Christian and Stanton (2004) found that burial offered some protection from predation, whereas Maron and Simms (1997) also found that burial significantly reduced the percentage of seeds removed by rodents.

Time of Sowing

Germination in native species from the southwest of Western Australia generally occurs during winter (June–August), when ample moisture is available and temperatures rarely exceed 20°C (Bell et al. 1995). Surprisingly, more emerged seedlings were observed from the May sowing than from the July sowing. The higher emergence rates from the May sowing may be due to the rains immediately following the May sowing. More than 40 mm of rain fell in the week following the May sowing, with an additional 150 mm recorded during the proceeding month. These periods of rainfall were also accompanied by milder temperatures, closer to optimal germination conditions as found by Bell et al. (1995). In comparison, following the July sowing, there was a period of 11 days without rainfall, followed by intermittent variable rainfall. The difference between May and July sowings may thus reflect the particular conditions during the experimental year, rather than a long-term trend of generally higher germination rates following sowing in May.

Alternatively, a later sowing may still have resulted in similar seed germination and seedling emergence as the May sowing. However, the later emergence in July may not have provided seedlings with sufficient growing and therefore establishment time. As a result, seedlings may have died prior to the October (late spring) scoring event (Roche et al. 1998; Rokich et al. 2000).

Conclusion

The results obtained in this study would indicate that the most effective combination for maximizing in situ seedling emergence following seed broadcasting is sowing coated seeds earlier in the growing season (such as May) and raking the soil after the seeds have been sown. A note of caution needs to be offered at this point though in that additional studies are needed to confirm the finding that earlier (May) rather than later (July) in situ seed broadcasting is optimal as unique conditions experienced during this study may have skewed the results presented here. What is not in contention is the fact that seed raking proved the most effective treatment for increasing emergence and has the benefit of being low cost and relatively straightforward to implement. However, it is worth noting that even for the most successful treatments, emergence rates were still substantially lower than one might ideally hope for. The fact that seed coatings showed some benefits in terms of emergence rates suggests that further manipulation of seed coatings such as the addition of various beneficial chemicals could further improve seed performance.

The results presented here provide the basis for improved land restoration practices utilizing a combination of polymer seed coatings and improved seed broadcasting techniques. However, to gain a better understanding of factors that need to be optimized to improve seed performance, further research needs to address not only a larger range of species but also a larger range of sites over a much longer time frame as newly established ecosystems are far from stable and need to be followed for a number of years to see which state they move toward.

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