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RESEARCH ARTICLE

Developing extruded seed pellets to overcome soil hydrophobicity and seedling emergence barriers

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Abstract

1. Globally, soil water repellency is a major constraint to plant establishment, restricting water infiltration and moisture retention in the seed zone which results in poor germination and seedling emergence.
2. To address this problem within an ecosystem restoration context, we investigated the use of a surfactant in extruded seed pellets to improve native plant recruitment in water-repellent topsoils of two proteaceous woodland species, *Banksia menziesii* R.Br (glasshouse trial) and *Lambertia inermis* R.Br (field trial). In this two-part study, we first examined *B. menziesii* seedling performance in detail under glasshouse conditions for differences in survival between the extruded pelleting formulations after an induced drought at 12 weeks.
3. We demonstrated that there was no difference in seedling emergence amongst control seed and pellet treatments in *B. menziesii*. Initially, *B. menziesii* seedlings emerged faster in the control treatment (non-pelleted control seeds) and had greater initial plant growth (leaf and root production), however by Week 12, seedlings generated from pellets were not significantly different from the control seeds and pellets + surfactant had the greatest number of leaf establishment.
4. Survival after drought of *B. menziesii* seedlings ranged from 14 to 31 days with pellet + surfactant surviving approximately 2.6 days (11.8%) longer than the control seeds. For the second species, *L. inermis*, seedling emergence under field conditions was approximately 24% greater in seedlings derived from extruded pellets; however, there was no difference in overall survival due to post-emergence predation.
5. This study provides a proof of concept that seedling emergence in water-repellent soils can be enhanced with extruded pellets containing surfactants. Our demonstration under in situ and ex situ conditions confirms the prospective use of seed enhancement technologies with future development and field-testing warranted.

KEYWORDS
Mediterranean ecosystem, planting techniques, restoration, revegetation, seedling emergence, surfactant, water repellency

1 | INTRODUCTION

Soil water repellency (SWR) can be a major constraint to plant establishment and growth (Ruthrof et al., 2019). As a global phenomenon (Dekker, Ritsema, Oostindie, Moore, & Wesseling, 2009; Doerr, Shakesby, & Walsh, 2000), it can negatively affect the establishment of plants in agricultural systems (DeBano, 2000), particularly during restoration (Madsen et al., 2012). Soil water repellence leads to decreased water infiltration and moisture retention in the upper soil profile often leading to poor germination and seedling survival (DeBano, 2000; Madsen, Kostka, Inouye, & Zvirzdin, 2012). Identifying, quantifying and mediating SWR is therefore central to improving establishment in agricultural or restoration systems.

Management options for SWR soils fall into three categories: amelioration, mitigation or avoidance (Roper et al., 2015). Commercially, SWR has been alleviated by developing soil wetting agents or surfactants (Dekker, Doerr, Oostindie, Ziogas, & Ritsema, 2001; Dekker, Oostindie, Kostka, & Ritsema, 2005; Moore, 1981) or the addition of substrates (e.g. clay) that increase water adsorption and transport. The application of surfactants has been found to increase the efficiency of water storage by soils, whether by increasing water retention in coarse textured soils or by improving water movement in water-repellent agricultural (Chaichi, Turcios, & Rostamza, 2016; Sullivan, Nuti, & Truman, 2009) and post-fire restoration soils (Madsen et al., 2012; Madsen, Davies, Boyd, Kerby, & Svejcar, 2016).

Despite considerable research, it remains a problem for which few mitigation technologies or solutions have been developed with success in agricultural or restoration activities (Ruthrof et al., 2019). Extruded pellets that contain soil surfactants is an emerging technology in restoration activities that is being developed to deploy and improve native plant establishment within degraded landscapes including overcoming SWR in North America's sagebrush biome (Davies, Boyd, Madsen, Kerby, & Hulet, 2018; Davies, Madsen, & Hulet, 2017; Madsen et al., 2016; Madsen et al., 2016). It is proposed that with the addition of a surfactant during the production of extruded pellets, and after it is sown in situ, precipitation leaches the surfactant from the extruded pellet into the soil, where is adheres onto soil particles and ameliorates water repellency within the immediate seed microsite (Madsen et al., 2016; Madsen et al., 2012).

High seedling mortality due to extremely water-repellent soils and drought are key limiting factors of restoration success in Western Australia and other Mediterranean ecosystems (McGhie & Posner, 1980; Padilla & Pugnaire, 2007; Roberts & Carbon, 1972). SWR need only to be temporarily alleviated to ensure successful establishment of plants and then SWR can be utilized to provide natural ecological benefits such as improving soil water conservation (Ruthrof et al., 2019).

This study investigated the incorporation of a non-ionic surfactant into extruded pellets to improve the initial stages of native seedling establishment. We used two proteaceous species (*Banksia menziesii* R.Br. and *Lambertia inermis* R.Br.) that occur in highly water repellent, deep sandy soils and are important components of Western Australian restoration. We aimed to improve the hydrological function of the microsite surrounding seeds with a surfactant, by improving soil water infiltration and retention, which will lead to enhanced seed germination and seedling survival. The objective was to ascertain if seedling emergence and early-stage establishment in water-repellent soils was greater from extruded pellets that did or did not contain a surfactant, when compared to directly sown seeds.

2 | MATERIALS AND METHODS

2.1 | Study species

B. menziesii and *L. inermis* were chosen for this study for several reasons. They are both (1) Proteaceous and key structural elements of the South West Mediterranean ecosystem, (2) used in ecological restoration areas containing highly hydrophobic sandy soils and (3) are costly ($0.75–$1.00 per seed; Nindethana, 2018). Revegetation with these wild sourced species is an expensive endeavour with low success rates from seeds of 5–7% (Turner et al., 2006); consequently, greenstock production and planting are the preferred method, though this results in a 10-fold higher cost (Rokich, 2016), and still a 7% survival rate after the second summer (Stevens, Rokich, Newton, Barrett, & Dixon, 2016). Therefore, increasing the plant establishment success from seeds is a high priority and investment in seed enhancement development could be a cost-effective approach if proven to be a successful tool.

2.2 | Extruded pellet production

All extruded pellets (hereafter referred to as pellets) contained a sterilized compost fraction (<2 mm), mixed with fine calcium bentonite (<0.2 mm; Bentonite Products WA Pty Ltd, Watheroo, Western Australia, Australia) and diatomaceous earth (<0.6 mm; 'Diatomite Fines', Mt Sylvia Diatomite Pty Ltd, Gatton, Queensland, Australia) powders, a water holding polymer (Stockosorb 660 Powder, Evonik Industries AG, Essen, Germany) and a fungicide powder (Captan 900WG, Mirco Bros Pty Ltd, Western Australia, Australia). For surfactant-treated pellets, a non-ionic soil surfactant (ASET-4001, Aquatrols Corporation of America, Paulsboro, NJ, USA) was incorporated with water and the fungicide powder (Madsen & Svejcar, 2016) (Table 1). The dry products and water were mixed in a TR-75 Pasta Machine (Rosito Bisani Imports, Los Angeles, CA, USA) to form a dough material that passed through a 19-mm diameter die and cut into 30 mm lengths.

While still moist, one seed per pellet of *B. menziesii* were inserted into 100 pellets for a glasshouse trial, and one seed of *L. inermis* were inserted into 270 pellets for a field trial. Pellets were then dried in a plant growth chamber (Plant Growth Chamber Biosyn series 6000, Contherm, New Zealand) at 40°C and 34% relative humidity for 12 hr and stored until sowing. The overall experimental control was individual seeds sown directly into the water-repellent soil.

TABLE 1 Extruded pellet formulation include weight (g) of wet and dry ingredients used, which produces a batch size of approximately 64 pellets

Ingredient	Weight (g)
Sterilized compost (<2 mm fraction)	180.00
Bentonite (<0.2 mm; Bentonite Milled E, Bentonite Products WA Pty Ltd)	139.40
Diatomaceous earth (<0.6 mm; Diatomite Fines, Mt Sylvia Diatomite Pty Ltd)	101.90
Water-holding polymer (Stockosorb 660 Powder, Evonik Industries AG)	15.00
Total dry weight	**436.30**
Captan (fungicide) (Captan 900WG, Micro Bros Pty Ltd)	1.20
Water	444.25
Non-ionic soil surfactant (ASET-4001, *Aquatrols Corporation of America*)	0.80
Total wet weight	**446.25**
Total weight	**882.55**

2.3 | Ex situ experiment (using *B. menziesii*)

A total of 150 pots (145 mm square-widths × 200 mm height) were filled with 4 L of water-repellent topsoil sourced from Hanson Construction Materials' Gaskell restoration site, 30 km north of Perth, Western Australia, Australia (31°45′ S, 115°55′ E). Pots were randomized within four replicate blocks that were set up in a glasshouse to assess seedling emergence of *B. menziesii*. The treatments were as follows: (1) directly sown seeds (control, n = 50); (2) seeded pellets (n = 50); and (3) seeded pellets + surfactant (n = 50).

We mimicked local rainfall events for the Mediterranean ecosystems of the area by taking the average monthly rainfall for the past 5 years over the period of this trial (57 mm August–November; Whiteman Park 009263 meteorological station (B.O.M., 2016)) and applied this amount of water to pots through an overhead irrigation system over 12 weeks. The simulated rain was applied twice weekly over this period and totalled approximately 60 mm per month. After 12 weeks, we applied a drought treatment, no watering for 6 weeks (when ambient temperatures reached up to 37°C).

2.4 | Ex situ SWR assessment

To determine the level of SWR in each treatment, three soil sampling harvests occurred post-sowing at 4, 8, and 12 weeks. One additional harvest occurred at 18 and 6 weeks after the induced drought. Six replicate pots from each treatment were selected randomly at each harvest. During each harvest, two soil cores were taken using a small core sampler (25 mm wide and 250 mm long); one adjacent to where the seed or pellet had been sown and one at the pots outer edge(~ 47 mm way from the seed) (Figure 1). SWR was measured on the cores at 6 and 12 cm depths (see Figure 1). A third soil core (40 mm wide and 240 mm long) was taken at the centre of the pot, surrounding where the seed or pellet had been sown. This larger core sampler was sectioned into three depths, surface (1–6 cm), middle (6–12 cm) and bottom (12–18 cm). This tested SWR that was (1) inclusive of the seed or pellet zone, (2) the zone immediately beneath the seed/pellet zone and (3) at the base of the pot. Initial SWR was tested using the Water Drop Penetration Time (WDPT) test, using the Dekker et al. (2001) and (2009) protocols for field-moist samples. Three drops of distilled water were placed on the surface of the core soil samples, using a standard medicine dropper, and the time until the drops penetrated into the soil was determined using a timer. Once WDPT measurements were performed on all cores, roots and plant material present were removed and bagged, central large cores were emptied into separate plastic containers and the containers of soil were sealed and weighed.

SWR was assessed at room temperature (26°C) and after drying the samples at 60 and 105°C as in Dekker et al. (2001). Soils were dried at 60°C to replicate the extreme soil temperature that can be experienced in Banksia woodlands during summer (up to 67°C; Merritt, Turner, Clarke, and Dixon, 2007). After each drying treatment, samples were weighed for gravimetric water content measurements. We measured SWR of all samples immediately after recording their weight under ambient laboratory conditions (i.e. 20–24°C / 50% relative humidity). We applied a seven-class index to quantitatively classify the persistence of SWR outlined by Dekker and Jungerius (1990); Class 0, wettable, non-water repellent (infiltration within 5 s), Class 1 (slightly water repellent (5–60 s); Class 2, strongly water repellent (60–600 s); Class 3, severely water repellent (600–3600 s); and extremely water-repellent Classes; 4, (1 hr), 5 (1– 3 hr); and 6 (>6 hr). Volumetric water contents were calculated using the gravimetric water content and the bulk density of each top core (0 – 6 cm) at Weeks 4 and 8 to calculate the water content present to each seed during the germination and emergence period.

2.5 | Ex situ seedling emergence and plant growth assessments

Emergence, number of true leaves and survival (after drought) were recorded every 2 days until all plants were harvested. Harvested leaves and roots at 4, 8, 12 and 18 weeks were measured using an EPSON Expression 11000XL photo scanner and analysed using imaging software (WinRhizo software v2007, Regent Instruments Inc. Quebec City, Canada). Leaves were measured for total surface area and total shoot surface area. Roots were partitioned into 10 diameter classes starting at <0.5 mm, to 0.5–1.0 mm, followed by increments of 0.5 mm until reaching >4.5 mm. The software debris removal filter was set to discount objects less than 0.2 cm^2 with a length/width ratio <5. Data for total root length, root surface area, root volume and diameter class length (root length within a diameter class) were generated (in WinRHIZO) from root images. Shoot and root tissues were then dried in a fan-forced oven at 80°C for 3 days and then weighed. Percentage emergence was counted on day 57 to replicate the in situ experiment.

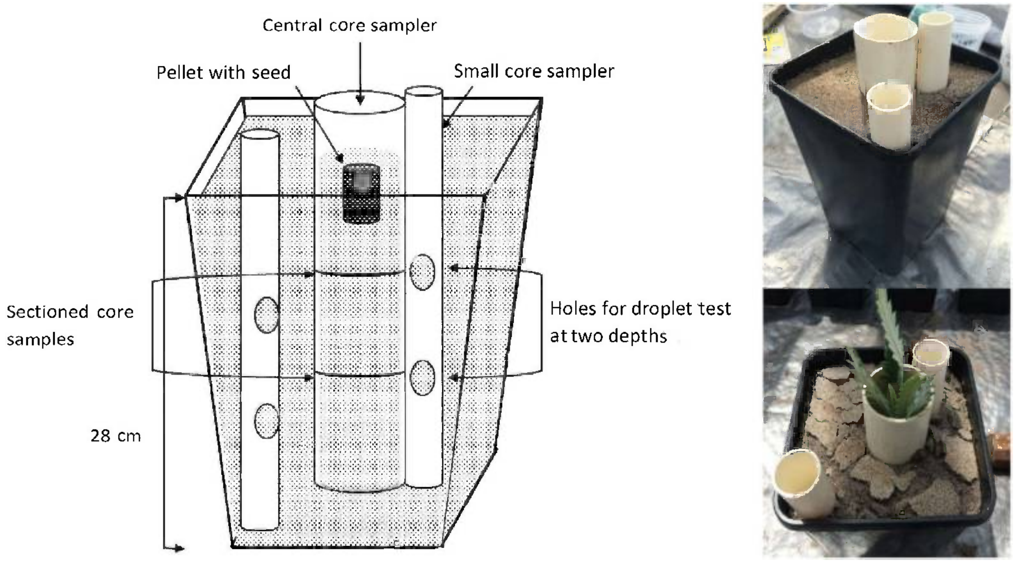

FIGURE 1 Glasshouse trial harvest pot design with core soil samples illustration (left) and photographs (right) of *B. menziesii*

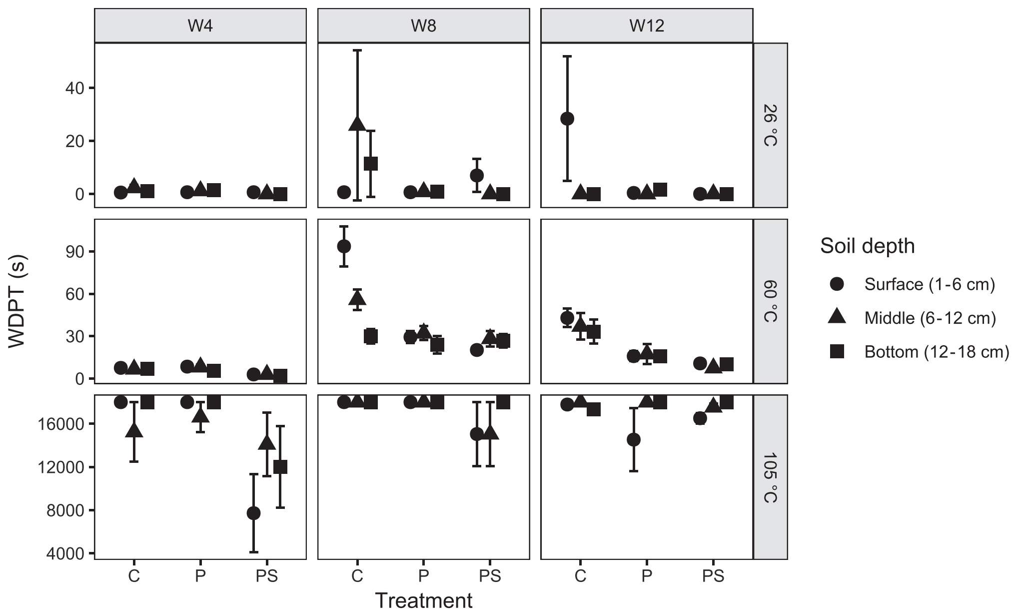

FIGURE 2 WDPT (seconds; 's') for surface (1–6 cm), middle (6–12 cm) and bottom (12–18 cm) depths of the pot at three different drying temperatures (ambient 26, 60 and 105°C) for each treatment after 4 (W4), 8 (W8) and 12 (W12) weeks* of *B. menziesii* seedling growth. Experiment treatments are as follows: C: direct sown seeds (control); P: pellet with seeds; PS: pellet with seeds + surfactant (ASET-4001). *at Week 18 pots contained completely dry soil after 6 weeks under drought

2.6 | In situ experiment (using *L. inermis*)

L. inermis seeds and pellets were sown into six plots (August 2016) within Bush Heritage and Greening Australia's Yarrabee Wesfarmers Reserve, 481 km south-east of Perth, Western Australia, Australia (34°19′S, 118°24′E). The site contained disturbed and intact areas of Proteaceous-rich heath shrubs on deep white sand and has been identified as having high SWR issues. The treatment design involved three seed sowing treatments (directly sown seeds, pellets with no surfactant, pellets with surfactant) within a disturbed area into six plots and one threat management treatment (fencing to prevent grazing) applied in alternating plots (2, 4 and 6). Fifty replicates of each treatment were sown in plots 1–4 and 35 replicates of each treatment were sown in plots 5 and 6 and monitored for seedling emergence throughout the first growing season. A limitation of this study was that replication was limited to one site. This was a result of logistical constraints and the

TABLE 2 Mean values ± SE of emergence, growth and survival parameters of *B. menziesii* and *L. inermis* seedlings. Volumetric water content (%) at 0–6 cm depth at Week 4 and 8 *B. menziesii* growing periods. Experimental treatments are as follows: Control: Direct sown seeds; Pellet: Pellet with seeds; Pellet + surfactant: Pellet with seeds + surfactant (ASET-4001)

Treatment	Control	Pellet	Pellet + surfactant	*P* value
Banksia menziesii				
Time to 25% emergence	20.50 ± 0.78	22.94 ± 0.28	21.69 ± 0.61	0.051
Time to 50% emergence	24.22 ± 0.67	25.73 ± 0.64	24.16 ± 0.99	0.423
Total emergence (%)	94.0 ± 2.37	96.4 ± 2.76	89.1 ± 5.16	0.374
Volumetric water content (%) Week 4	11.74 ± 1.18[a]	23.82 ± 1.80[b]	26.59 ± 4.05[b]	0.006**
Volumetric water content (%) Week 8	12.43 ± 1.35[a]	20.04 ± 1.79[b]	19.70 ± 1.37[b]	0.008**
Leaf number[1] at 45 days	2.19 ± 0.16[a]	1.42 ± 0.10[b]	1.57 ± 0.11[b]	< 0.001***
Leaf number[1] at 90 days	6.62 ± 0.18	6.83 ± 0.19	7.38 ± 0.29	0.052
Survival post drought (days)	22.0 ± 0.67[a]	23.5 ± 0.68[a,b]	24.6 ± 0.87[b]	0.024*
Lambertia inermis				
Total emergence (%)	37.2 ± 7.84[a]	58.1 ± 3.71[b]	58.8 ± 5.01[b]	<0.001***
Survival of seedlings (%)[2]	0 ± 4.99	3.45 ± 2.97	3.63 ± 2.82	0.645

P value, ****P* < 0.001, ***P* < 0.01, **P* < 0.05; $\alpha = 0.05$ Different lower case letter indicates statistically significant differences at $\alpha = 0.05$, multiple comparison test with Tukey contrasts.
[1]True leaf number after production of cotyledons.
[2]High mortality due to pest damage.

reliance of community members to install the trial in the remote field site south of Perth. To minimize any effect at the plot-level, pellets were sown 60 cm apart from each other to act as individual replicates within the broader plot layout. Although we cannot completely rule out the potential of the single site confounding some of our results, we believe that any main effects observed would come from the seed/pellet treatment level.

2.7 | Statistical analysis

One-way analyses of variance (ANOVAs) were carried out on emergence and measurements of above and belowground growth, average leaf surface area, average root length (cm) and average root surface area (cm^2) for the *B. menziesii* trial. One-way ANOVAs were performed for the volumetric water content sampled from Weeks 4 and 8. Where required, data were log transformed to meet the assumptions for ANOVA analyses. Tukey's honestly significant difference (HSD) test was calculated for multiple comparisons of the mean values for each treatment.

Given the reduced level of replication at the *L. inermis* trial site, generalized linear models (GLM) fitted with a binomial distribution were used for emergence and survival to use each pellet as a replicate. *P* values were obtained using the Likelihood Ratio Tests by comparing the full model against a null model, using the *anova* function. All statistical analyses were conducted using R statistical environment version 3.6.1 (R Core Team, 2019) within RStudio (RStudio, 2018) using packages *lmtest* (Zeileis & Hothorn, 2002), *emmeans* (Lenth, 2018) and *multcomp* (Hothorn, Bretz, & Westfall, 2008), and plots were generated using *ggplot2* (Wickham, 2016).

3 | RESULTS

3.1 | Ex situ SWR and soil water content assessment

At the time of sowing, the average WDPT of the soil was over 4 hr, indicating extreme water repellency (Figure 2). All soils harvested at Weeks 4, 8 and 12 were classified as Class 0 and 1, being wettable (non-water repellent, infiltration within 5 s) to slightly water repellent (5–60 s). After drying at 60°C, WDPT became more variable between treatments and time to infiltration increased, with Weeks 8 and 12 in Class 1 and 2. Water infiltration times were higher for control seeds (C) in Weeks 8 and 12 had in comparison to the pellet treatments. After soil was completely dry (105°C), all soil samples were extremely water repellent (Class 5, 3–6 hr), with only pellet + surfactant (PS) indicating lower infiltration times (Class 4, 1–3 hr) (Figure 2). Volumetric water content (%) was significantly greater within soil cores from the seed zone in pots containing a pellet (with and without a surfactant, P and PS) than from pots with control seeds (C) at both Week 4 and 8 (Table 2, Figure 3). No significant differences were found in volumetric water content (%) within soil cores from the root and root elongation zones between treatments (Figure 3). At 18 weeks, and 6 weeks post-drought, all pots were completely dry.

3.2 | Ex situ and in situ seedling emergence

Pelleted seeds of *B. menziesii* emerged marginally slower from the soil (time to 25% emergence (T_{25}) was 5.8–11.9% slower in the pelleted treatments P and PS; Table 2), than the non-pelleted seeds (C). By

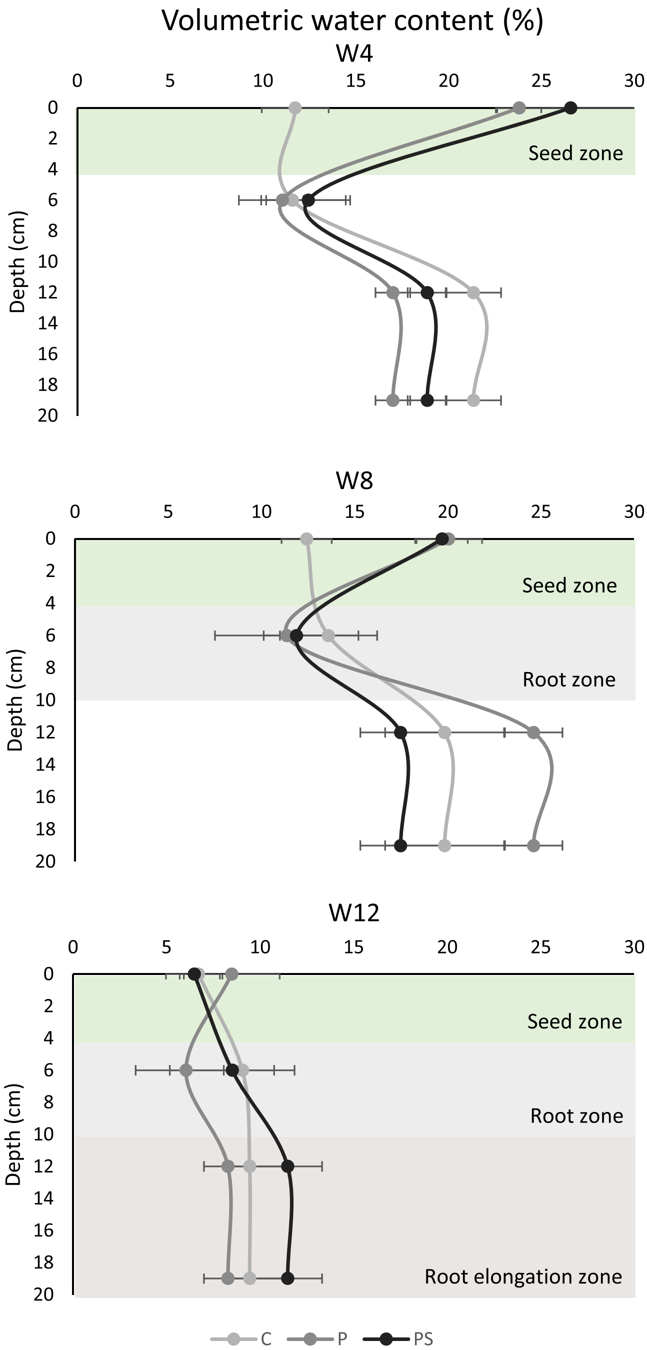

FIGURE 3 Vertical profiles of the distribution of volumetric soil moisture content (%) of treatments after 4 (W4), 8 (W8) and 12 (W12) weeks of *B. menziesii* seedling growth. Experiment treatments are as follows: C: direct sown seeds (control); P: pellet with seeds; PS: pellet with seeds + surfactant (ASET-4001). ± SE indicated by error bars. Zone labels indicate areas of plant growth during Weeks 4, 8 and 12

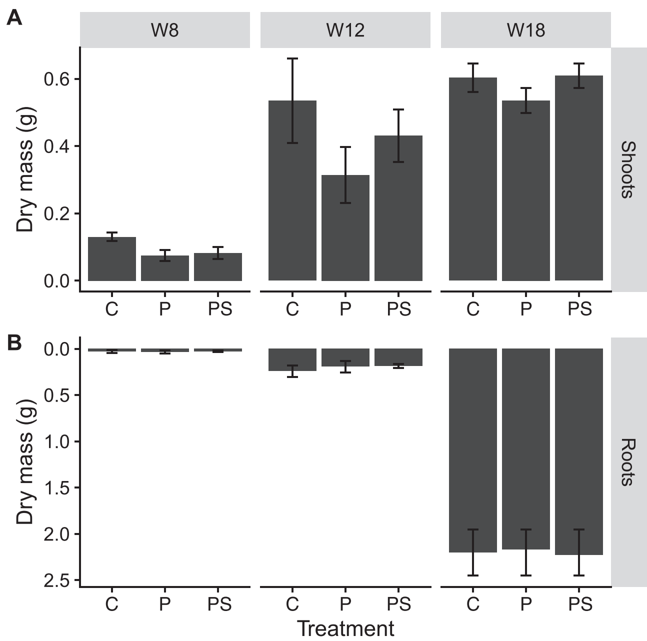

FIGURE 4 Mean shoot (A) and root (B) dry mass (g) ± SE of *B. menziesii* seedlings grown within different treatments after 8 (W8), 12 (W12) and 18 (W18) weeks. C: direct sown seeds (control); P: pellet with seeds; PS: pellet with seeds + surfactant (ASET-4001)

the time emergence reached 50% (T_{50}), there was no difference. At 57 days, there was no difference ($F_{2,9} = 1.10$, $P = 0.374$) in percentage emergence of *B. menziesii* seedlings amongst control seeds (C = 94%), pellets (P = 96%) and pellets + surfactant (PS = 89%). For the field study, at Day 57, seedling emergence of *L. inermis* was greater (GLM, $P < 0.001$) from pellets ± surfactant (P = 58%, PS = 59%) in comparison to the control seeds (C = 37%) over all treatments (fenced and unfenced) (Table 2).

3.3 | Ex situ plant growth assessment

At the first sign of true leaves (45 days), the control *B. menziesii* seedlings (C) had significantly higher mean number of true leaves than pelleted seedlings ($F_{2,64} = 8.96$, $P < 0.001$) (Table 2). At the cessation of leaf production post-drought (90 days), pellets (P) were not significantly different from the control seeds, and pellets + surfactant (PS) had the greatest number of true leaves (Table 2). At Week 8 and 12, the control seeds (C) had greater shoot mass in comparison to the pelleted treatments (P and PS) (Figure 4); however, by Week 18 there were no differences between treatments. Root biomass did not differ between treatments across the 18 weeks (Figure 4). No differences were found between treatments for any of the root measurements: diameter classes, volume (data not shown), total length and surface area (Supplementary Information Figure S1).

3.4 | Ex situ and in situ seedling survival assessment

After imposing a drought treatment in the glasshouse at 18 weeks growth of *B. menziesii* seedlings, survival ranged from 14 to 31 days (post-drought), with pellet + surfactant surviving approximately 2.6 days longer than the control seeds (Table 2; Figure 5). No seedlings

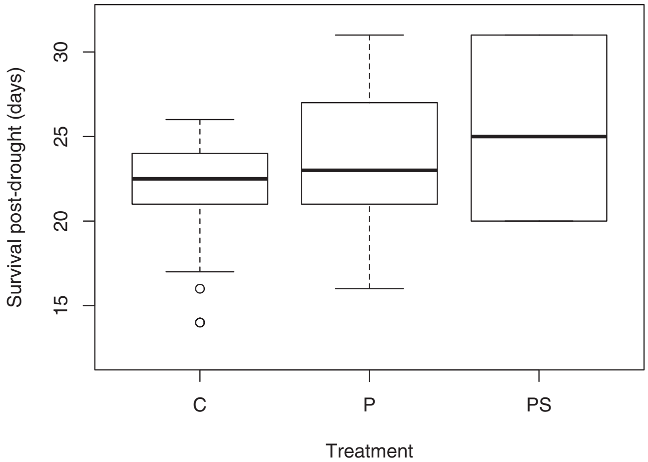

FIGURE 5 Mean survival (days) post-induced drought at 12 weeks of *B. menziesii* seedlings grown within different treatments. C: direct sown seeds (control); P: pellet with seeds; PS: pellet with seeds + surfactant (ASET-4001). Significant differences between treatments were identified using post-hoc tests; treatments that do not share a letter showed significant variation ($P < 0.05$)

of *L. inermis* survived in the unfenced plots due to grazing (kangaroos) and damage by Red-legged earth mites (RLEM, *Halotydeus destructor*), and of those that survived in the fenced plots (<5%), there was no difference in survival between treatments (control seeds, pellets and pellets + surfactant) (Table 2) due to the RLEM damage.

4 | DISCUSSION

Enhancing microsite conditions to promote seedling emergence is essential to restoration projects, especially considering the predicted drying climatic conditions in Mediterranean ecosystems (Bates, Hope, Ryan, Smith, & Charles, 2008). This study provides a proof of concept that the establishment of woodland species in water-repellent soils can be enhanced using seed pellets. Our demonstration under in situ and ex situ conditions highlights the prospective use of seed enhancement technologies, particularly the use of surfactants and extruded pellets, to overcome limitations to restoration success.

Higher early-stage recruitment success (i.e. increased germination and emergence proportions) has been shown to be a strong predictor of overall survivorship (Leger, Atwater, & James, 2019) and greatly improves restoration outcomes (James, Svejcar, & Rinella, 2011). Therefore, any treatments that promote higher or earlier recruitment are likely to benefit many seeding efforts. The observed 20% increase in seedling emergence in *L. inermis* from pellets used in this study suggests that the immediate seed–soil microsite was enhanced under field conditions. Whether this was due to a break down in water repellency or other in-direct benefits of moisture capture, such as moisture wicking from deeper soils layers (Madsen et al., 2016), warrants further investigation.

Further, extruded pellets provided a favourable medium for seedling emergence, early-stage establishment and growth in *B. menziesii*. Though early life stage demographic processes differed somewhat for un-pelleted *B. menziesii* seeds (i.e. slightly higher above ground growth in Weeks 4–12), by Week 18, there were no differences in growth performance measured. That is, all seeded and pelleted treatments displayed comparable emergence values and seedling characteristics at the juvenile life stage and some evidence of improved drought tolerance. These findings support our study objective that extruded pellets, and the potential targeted use of soil surfactants, can aid early-stage seedling recruitment.

SWR in this Mediterranean environment is a common occurrence (Ruthrof et al., 2019); it can be severe to extreme (WDPT over 5 hr (Muñoz-Rojas et al., 2016)) and is therefore the primary barrier that we aimed to overcome in this study. Although no distinctive trends indicated that the pellet treatments altered SWR on these soils, there were some specific positive responses. For example, volumetric water content was significantly higher within the seed zone (0–6 cm) of pots containing pellets, indicating the advantageous benefits that pellets, with or without surfactants, have in providing greater moisture during the initial critical growth stages (at Weeks 4 and 8). This finding is consistent with similar native seed enhancement research in the western deserts of the USA, where surfactants have been shown to improve moisture percolation and retention around the seed zone (Madsen et al., 2012). Further, replicating the soil temperatures reached in *Banksia* woodland soils (60°C; Merritt et al., 2007) we start to see some influence of pellets with a surfactant on SWR, with lower WDPT in Weeks 8 and 12. After full drying (105°C) of soils at Weeks 4 and 8, there is some positive effect of the pellet with a surfactant in reduced WDPT and therefore SWR.

Seedling survival is one of the most critical stages in a plant's life history and is often terminated by drought and soil drying (Padilla & Pugnaire, 2007). Pellets marginally improved ex situ survival (<3 days longer) of *B. menziesii* seedlings in a post-drought experiment. While seedlings only persisted marginally longer post-drought, the capacity to extend the seedling survival window is a promising result. In our study, the average survival percentage of *L. inermis* seedlings was marginally higher in pellets ± surfactant, when compared to un-pelleted seeds under field conditions. Further, seedlings of *B. menziesii* growing from pellets had slightly higher survival in drought conditions. Therefore, there is some evidence to suggest that there could be prolonged moisture retention around the root zone promoting juvenile survival. Future studies need to consider how longer-term, non-destructive measures can be used to map this moisture retention. Accurately measuring soil moisture dynamics is now feasible (Steele-Dunne et al., 2010), and one approach is to use high-resolution mapping of soil moisture and properties using distributed temperature sensing (DTS) data. Testing different pellet formulations and investigation into pellet moisture patterns using technologies such as DTS warrants further study.

There is a host of potential studies that can be done to refine and improve the efficacy of these pellets. Some studies, for instance, have recently suggested that pellets could be redesigned to overcome un-desired properties (Clenet, Davies, Johnson, & Kerby, 2019; Davies et al., 2018; Madsen, Svejcar, Radke, & Hulet, 2018). In the process of making pellets, for instance, the dough that is formed can be created with a multitude materials, that depending on species and site conditions (i.e. clays, binders, inoculums, bio stimulants) can be tailored to aid in seed germination, seedling emergence and early plant growth (Madsen & Svejcar, 2016; Madsen et al., 2016; Ruthrof et al., 2019). From this initial pilot study, optimal testing of surfactants (e.g. surfactant concentrations) and other products used to reduce SWR need examination for their efficacy, their incorporation into pellets and their impact on native plant establishment (Müller & Deurer, 2011).

In this study RLEM (*H. destructor*), an introduced pest of agricultural lands in Australia, extensively damaged the *Lambertia* field trial seedlings. Additions of insecticides, pesticides and/or systemic insecticides to the pellets could potentially eliminate this next limitation to survival and help the *Lambertia* seedlings transition to the next life stage (James et al., 2011).

Further investigation into the development of products to help ameliorate SWR at the micro-scale is required (Ruthrof et al., 2019). With greater knowledge of this abiotic barrier arising, there are greater innovative opportunities to refine seed enhancement technologies. Investigation into the application of seed enhancement technologies to address later-stage seedling dynamics such as to improve seedling establishment and plant survival by overcoming herbivory is also warranted. Our results indicate that pellets may improve the emergence and establishment of native shrub/tree species that are grown in unfavourable hydrophobic environments undergoing restoration. The application of this restoration seeding approach may enhance the establishment of species that do not exist in the soil seed bank or where soil seed banks are not an available resource, by providing a favourable microsite for germination and a longer window of moisture for survival during soil drying.

AUTHORS' CONTRIBUTIONS

AR, JS and TE conceived and designed the research; AR performed the glasshouse and laboratory experiments and analysed the data; AR, JS and TE wrote and edited the manuscript.

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.q2bvq83h1 (Ritchie, Stevens, & Erickson, 2020) and The University of Western Australia Repository https://doi.org/10.26182/5f44645fe0bb6 (Ritchie, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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