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A case study of seed-use technology development for Pilbara mine site rehabilitation

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Abstract

Mine rehabilitation is not just earthworks. Mine rehabilitation is a complex, integrated process that involves multiple stakeholders, long-term commitment, and a comprehensive understanding of site-specific conditions. When it comes to the re-introduction of vegetation, increasing the likelihood of successful plant establishment requires the proper implementation of many components including growth media movement, land forming, seedbed preparation, and seed delivery.

From a perspective of initiating plant recruitment, best practice use of native seeds is fundamental, and seed technologies can also be coupled with the invention, development and modification of the seeding equipment needed to deliver seeds at scale. Improving seed-use efficiency through seed-enhancement technologies is one approach that has gained recent attention in dryland rehabilitation. Techniques including precision flash flaming, priming, polymer-based seed coating, and extruded seed pelleting all aim to improve the germination and establishment potential of seeds under suboptimal conditions. Along with modifications to existing mechanical seeders or with new builds, these technologies are one potential solution to overcome inefficiencies in dryland seeding efforts. For instance, through the fabrication and engineering of new parts fitted to existing seed-coating equipment, 'flash flaming' is a technique that removes unwanted hairs and appendages off bulky and fluffy seed batches (e.g. spinifex or Triodia species). After removal, seed batch volume is significantly reduced, while the flow properties of seeds through cleaning equipment and mechanised seeders are vastly improved.

In this paper, we highlight some key examples of recent approaches to addressing shortfalls in seedling establishment in the mining-intensive Pilbara region of Western Australia. We detail research findings that highlight the benefits of flash flaming of seeds for Australian and American species, the application of polymer-based seed coatings and seed priming, and discuss how collaborations between environmental scientists and mechanical engineers have progressed the application of seed-based technologies for rehabilitation across large-scale, high-impact mining scenarios. Outcomes of these programs are applicable to degraded lands requiring rehabilitation across Australia, the United States of America, and other dryland regions.

Keywords: *rehabilitation, mine closure, seed-enhancement technologies, engineering solutions, Pilbara*

1 Introduction

Mine rehabilitation is a complex, integrated process that involves multiple stakeholders, long-term commitments, and a sound understanding of site-specific, biotic and abiotic conditions (Doley et al. 2012; Lamb et al. 2015; Gastauer et al. 2018). While a rehabilitation site is only available once it is released from mine production to the rehabilitation department, the rehabilitation process involves progressive planning throughout the exploration, construction, development, and mining operations (Department of Mines, Industry Regulation and Safety 2015). Upon handover of a site for rehabilitation, extensive planning and engineering design of landforms is carried out, either internally or through outsourcing to the private sector. Specific design considerations for each rehabilitation site include the slope angle, length, and growth media competency of the landform, all of which take into account a range of environmental and geomorphological conditions through detailed landscape evolution modelling (Hancock 2004). These steps are critical to ensuring the final constructed landform is safe, stable, and non-polluting. Considerable earthworks and material movement is then commissioned involving coordination among multiple internal departments (e.g. mine planners, geologists, closure specialists, and rehabilitation advisors) and external parties (e.g. rehabilitation and soil scientists). To increase the likelihood of successful ecological rehabilitation (i.e. establishment of a perennial plant community comparable to the pre-disturbed landscape), the implementation of many components is required including growth media movement, land forming, seedbed preparation, and seed delivery. Mine rehabilitation is not just earthworks.

Over the past 10 years, multiple research, industry, and government partners have been working on various aspects of mine rehabilitation practices in the mining-intensive Pilbara region of northwest Western Australia to enhance rehabilitation capacity to deliver measurable improvements in soil- and plant-based conditions (Erickson et al. 2016a, 2016b, 2017). These projects have begun addressing techniques for overcoming soil-based limitations to plant growth and the recovery of soil quality and health (Muñoz-Rojas et al. 2016a, 2016b; Bateman et al. 2018). A major goal of these projects is to enhance the biodiversity and ecological functions (e.g. reducing soil erosion and promoting perennial plant establishment) of rehabilitation sites by improving the use of native dryland species. These industry-funded initiatives (Price 2015) require long-term integrated and multi-disciplinary collaborations involving not only seed scientists and soil ecologists, but mechanical and agricultural engineers, small-to-medium enterprises, local seed suppliers, and direct seeding contractors to successfully address the challenges of large-scale rehabilitation.

In this paper, we focus on highlighting our recent advances and research approaches to increase the efficiency of seed-use through seed-enhancement technologies for dryland rehabilitation (Guzzomi et al. 2016; Madsen et al. 2016a; Erickson et al 2017). Seed enhancements including precision flash flaming, priming, polymer-based seed coating, and extruded seed pelleting all aim to improve the germination and establishment potential of seeds including under conditions that may be suboptimal for regeneration. Partnering these seed technologies with modified or newly engineered mechanical seeders that allows for precision placement of diverse types of native seeds across the sloped and rocky landforms on mine sites represents one potential solution to existing inefficiencies in dryland seeding efforts where often over 90 percent of seeds fail to establish (James et al. 2013; Erickson et al. 2017) (Figure 1).

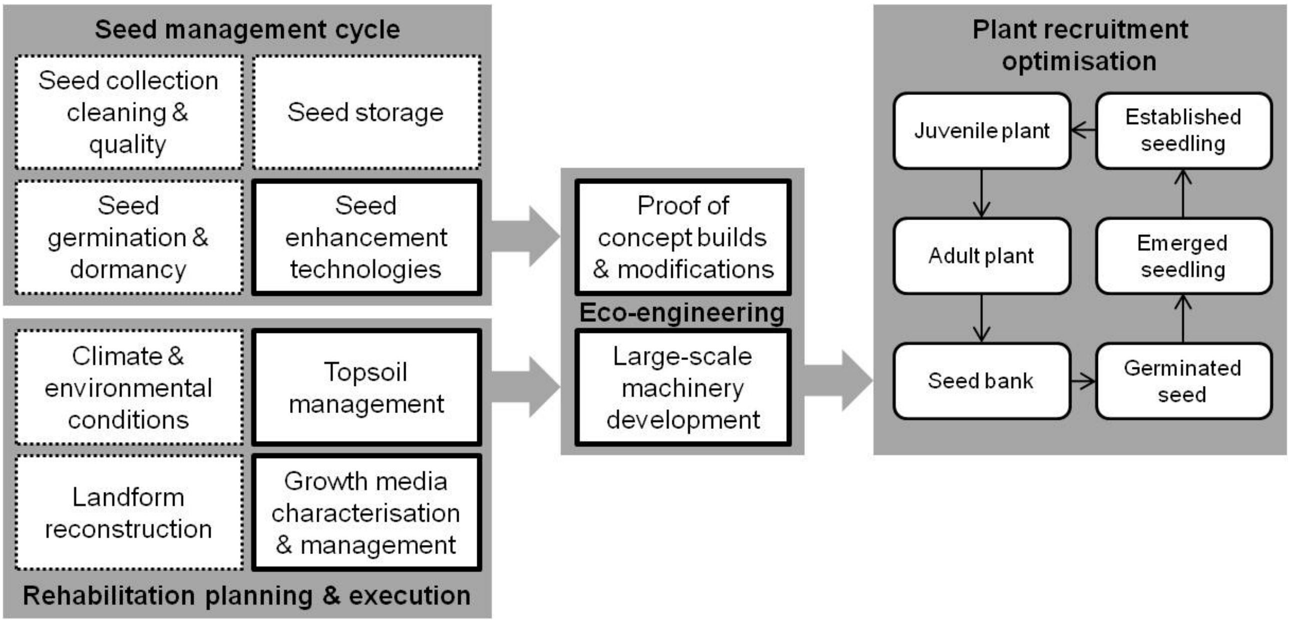

Figure 1 A conceptual model of mine site rehabilitation detailing the components that contribute to re-establishing plant communities at a landscape-scale. The seed management cycle is implemented in unison with rehabilitation planning and execution. However, further development is needed to efficiently deliver seeds to reconstructed soil environments. Current research aims to deliver on these components focusing on the highlighted solid-bold boxes and transitional grey arrows above

2 Seed-enhancement technology development for use in arid ecosystems

Seed-enhancement technologies are defined as any post-harvest treatments applied to seeds to enhance seeding, germination, emergence, and/or establishment (Taylor et al. 1998; Madsen et al. 2018). Enhancement technologies such as seed coating and seed priming have long been used to improve seed germination in crop and horticultural species (Paparella et al. 2015). Recent research has focused on applying these technologies to wild-collected, native seeds needed for rehabilitation efforts such as large-scale seeding in the desert ecosystems of the United States of America (USA) and mine rehabilitation programs in Western Australia (Abella et al. 2015; Guzzomi et al. 2016; Madsen et al. 2016a, 2016b; Erickson et al. 2017; Kildisheva 2019).

Broadly, there are four specific areas being targeted to improve the establishment potential of seeds in mine rehabilitation in the Pilbara:

1. **Polymer seed coating:** this process involves applying fine-grained soil/mineral products and binding agents (i.e. polyvinyl polymers and glues) to seeds in successive steps. Once coated, seeds are more uniformly shaped and sized and are more amenable to mechanised seeding. Other benefits of polymer seed coating include the ability to inoculate the coating materials with germination stimulants and herbicides, and chemical or biological agents that assist in early seedling establishment.

2. **Extruded seed pelleting:** the pelleting process is similar to polymer seed coating, except it embeds seeds in various soil and/or organic-based products. The pellet may consist of larger quantities of several soil or mineral products, water-holding gels, beneficial organic matter, and chemical agents moulded into a seed-soil-matrix. The pelleting process involves mixing the seeds and pellet ingredients into a wet dough and extruding the material through a mechanised extruder. Once dried, typical pellets are approximately 8 mm in diameter and 15 mm long, and may contain one or

more seeds, depending on the desired seed densities. Variations to pellet size and shape are easily achieved depending on the size of the targeted seeds.

3. **Seed priming:** seed priming involves the controlled hydration of seeds to commence, but not complete, the germination process (i.e. increased metabolic activity). Prior to radicle emergence (i.e. germination), seeds are removed from the priming conditions and re-dried to arrest germination. Primed seeds display more uniform and faster germination and enhanced stress tolerance – properties that may increase establishment potential.
4. **Precision flash flaming:** flash flaming involves the controlled removal of undesired fruit/seed appendages by repeatedly passing fruits/seeds past a stationary flame inside a drum. A rotating base inside the steel drum allows seeds to move freely around the drum wall at high speeds. Removal of unwanted appendages increases the bulk density of the seed batch, promotes the adherence of artificial seed coatings, improves flow-through direct seeding machinery, and even enhances germination of some seeds that have complex dormancy mechanisms.

Below are some examples of how these seed-enhancement technologies have been evaluated and developed for use in mine rehabilitation programs in the Pilbara.

2.1 Example 1: polymer seed coating evaluations and the initial development of flash flaming

The first seed-coating trials on *Triodia wiseana*, a dominant grass of the Pilbara region, exposed the problematic nature of the hairs and awns common to its florets and those of other grasses. These appendages reduced the integrity of the polymer seed coat (Figure 2A) and precluded applying coating technologies to these types of seeds. Utilising a small-scale, 350 mm, seed-coating drum, novel flaming treatments were developed and trialled to determine whether the awns and hairs could be removed by a brief exposure to naked flames derived from a propane torch, without decreasing the germination potential of the florets (Ling et al. 2015; Guzzomi et al. 2016). Results demonstrate that hairs can be completely removed and the awns reduced (Figure 3), thereby increasing the integrity of seed coatings (Figure 2B). Through optimising the flaming treatments, subsequent germination of the seeds was not affected and at times, increased the germination potential.

This flash flaming technique continues to be advanced through the fabrication of new parts and machines, allowing many more species that have been historically hard to handle and/or deliberately avoided, due to their surface features, to be used in large-scale rehabilitation programs (Section 2.2).

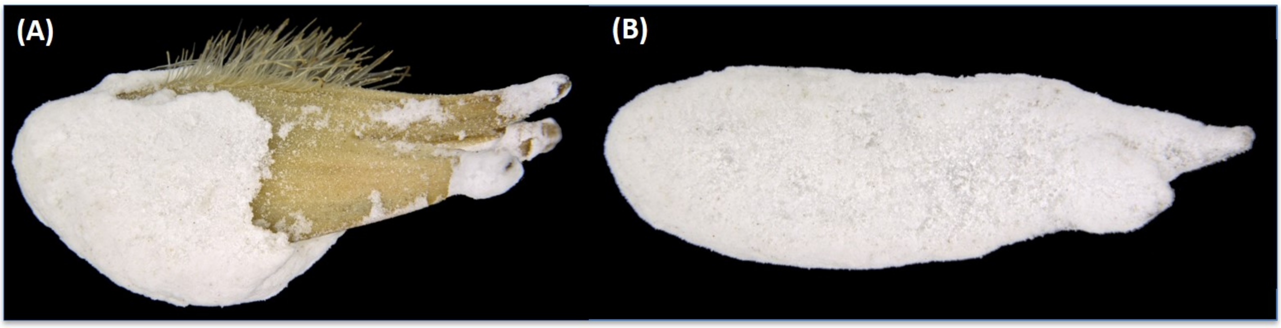

Figure 2 Triodia wiseana florets coated with a layer of calcium carbonate powder, which is a base ingredient for many types of coatings. (a) The integrity of the seed coat on un-flamed florets is reduced due to the floret hairs and awns interfering with the uniformity of the coat; (b) Once the florets are flamed, the coating can be applied uniformly and remains intact

Figure 3 Triodia wiseana florets exposed to flaming of between 0–10 mins. Florets were exposed to the flame while rotating within a seed-coating drum. The photos illustrate the progressive removal of floret hairs and reduction in awn length, creating seed readily useable by seeding machinery

2.2 Example 2: scaling-up the development of flash flaming for commercial uses

To scale-up the flash flaming technology to allow for the treatment of commercial quantities of seeds for large-scale rehabilitation, a 900 mm diameter flash-flaming drum was designed and built (Figure 4). The effectiveness of this larger drum in removing unwanted hairs and awns has been tested on 10 species from the Pilbara, primarily on species of *Triodia* and *Ptilotus*, to understand whether this unit could, when treating larger quantities of seeds, produce similar decreases in volume and weight, and improve 'flowability' (i.e. the ability of seeds to flow-through machinery without getting stuck) as seen using the smaller experimental unit (Section 2.1). This technology is also being developed for desert ecosystems in the USA and to date, eight species have been tested in the USA spanning plant families (i.e. Poaceae, Asteraceae, and Chenopodiaceae) that are common throughout the Pilbara.

Figure 4 The newly constructed flash flaming apparatus contains a dual-flame set-up and features that allows the control of the airflow, rotation speed of the base plate, and removal of flamed material through the hopper shoot after flaming is complete

The large-scale flash flaming machine can comfortably remove the hairs and awns in the same manner as the smaller experimental unit but can handle larger batches. In many cases, most of the volume reduction that is possible occurred within 5–10 mins of treatment, albeit through responses dependent upon the original amount and type of unwanted appendages present on the florets. After 30 mins of flaming, a 20–60% volume reduction and up to a 30% decrease in mass was achieved in all but one species. Combined with the decreases in volume and weight of flamed material, the level of flowability increased considerably.

Commercial-scale batches (e.g. 50–100 kg) of flamed material have now been tested through two air-seeder drum units commonly used across mine rehabilitation programs in the Pilbara region of Western Australia (Figure 5A). Recent evaluations of seed delivery in these field trials confirmed that flamed florets of a three species *Triodia* mix (i.e. *Triodia pungens*, *T. basedowii*, and *T. lanigera*) flowed better and more consistently when compared to unflamed material (Figure 5B). For instance, as each of the four seed slot/drum apertures were progressively widened from 10 to 30 mm, the flow rates of the flamed material exponentially increased from < 2 kg/hr to over 35 kg/hr (blue diamonds, Figure 5B). Whereas, the flow rate of the unflamed material did not exceed 10 kg/hr at any of the aperture settings (red squares, Figure 5B). Seeding with flamed florets overcomes issues of inconsistent and reduced flow of large, 'fluffy' batches of *Triodia* florets.

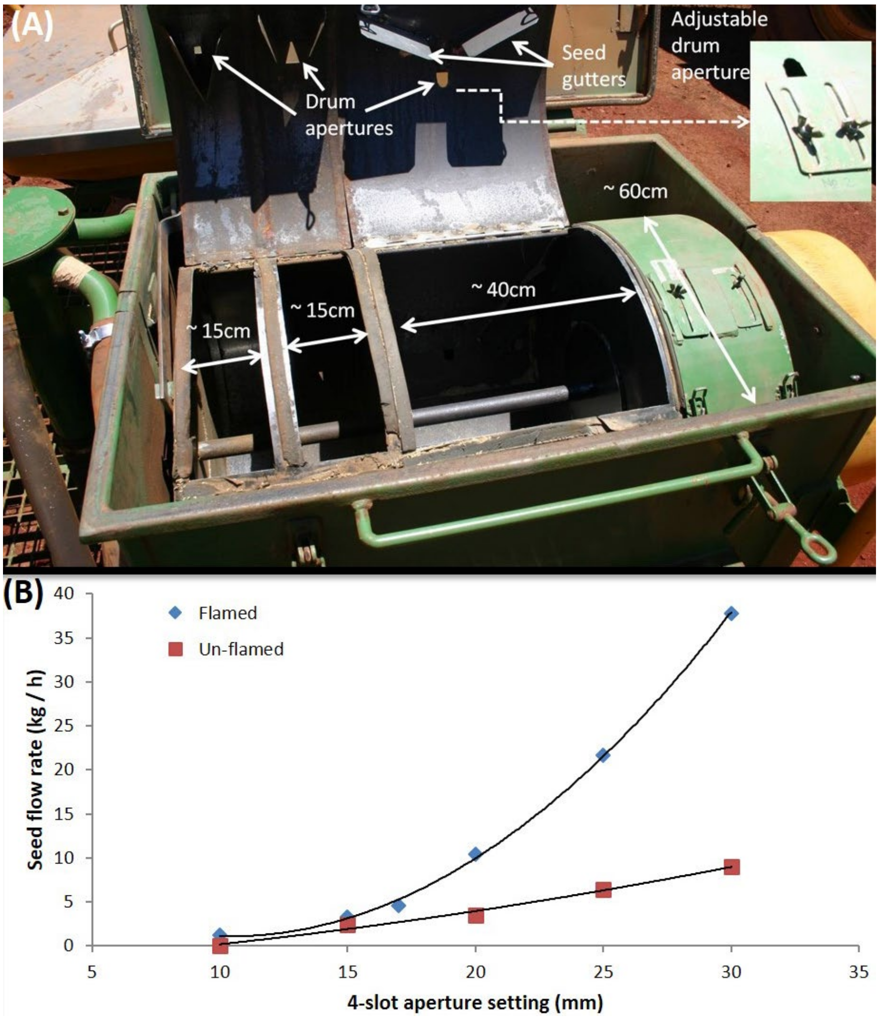

Figure 5 **Air-seeder drum units are commonly used in the Pilbara and Goldfields regions to distribute florets/seeds of a range of species and sizes. (a) Typically, large and fluffy batches of seeds (e.g. Triodia florets) are placed in the largest drum compartment. Through the trial and error of a seed contractor, the adjustable drum apertures are opened to achieve the desired seeding rate (e.g. 4–6 kg/hr). (b) However, fluffy material has a lower and inconsistent flow rate, resulting in little change in the kilograms of material delivered per hour across a range of aperture settings (red squares). Once flamed, seed batches are uniform in size and shape and the material flow increases with aperture size, in an almost exponential manner (blue diamonds)**

2.3 Example 3: development of extruded seed pellets using various mineral products

Initial trials on extruded seed pelleting have focused on the different mineral products used in the pellet recipe and the potential influence of mixing duration on pellet traits that could influence the mechanised delivery and emergence potential of seeds under field conditions. In this example, three different mineral products were trialled to create the pellets:

1. Calcium carbonate.
2. Diatomaceous earth.
3. 'Oil-Dri' (a commercial bentonite product from the USA derived from the mineral attapulgite).

These products were added to the pellet recipe in pairs, resulting in three combinations of pellet recipes. Preliminary assessments of the dough extrusion process indicated that the pellets extruded later in the extrusion process (after the first 15 mins) were denser than the initial pellets. Therefore, two extrusion times, 0–10 mins and 10–20 mins, were assessed. Pellet 'hardness' was measured using an Instron that measured the compressive forces required to fracture an individual pellet (Figure 6A). Water-holding capacity was assessed by measuring the increase in weight after placing the pellets in water (Figure 6B). Seedling emergence was assessed by sowing the pellets in seedling trays maintained at field capacity (Figure 6C and D).

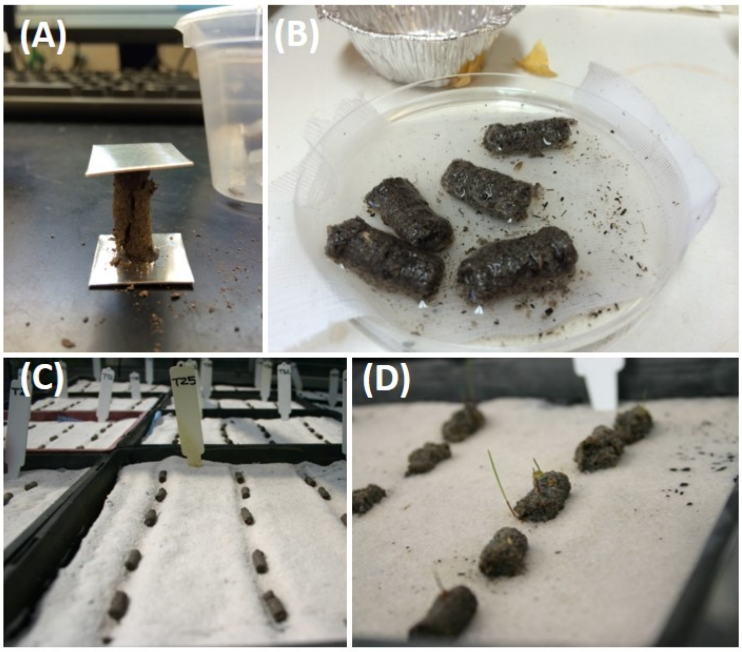

Figure 6 (a) A fractured pellet after compression testing and (b) swelling pellets during water uptake. Measurements used to determine the 'hardness' and water-holding capacity of the pellets, respectively. (c) Pellets were also sown in seedlings trays in the glasshouse and watered daily to maintain close to field capacity. (d) Seedling emergence was measured daily for 15 days

Considerable differences in the 'hardness', water-holding capacity, and emergence potential of seeds in pellets were evident between the tested mineral product combinations and extrusion times tested (Figure 7). Pellets that contained the locally-sourced clay bentonite consistently required higher compressive forces to fracture (Figure 7A). Further, there was approximately a 15–20% difference in the seedling emergence potential of pellets, with the pellets produced earlier in the extrusion process having higher seedling emergence percentages, regardless of the pellet composition (Figure 7B). These initial studies highlighted that both mineral product and extrusion time influence the pellet properties. Ongoing modifications to the pellet production process has continued to evaluate alternative mineral products and extrusion methods to ensure pellet properties allow for mechanical delivery while maximising plant establishment under field conditions.

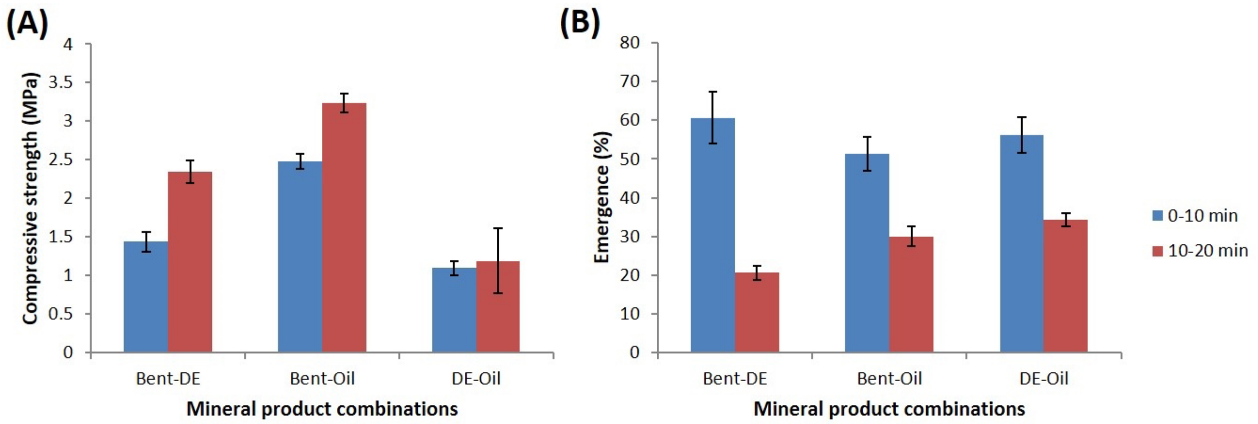

Figure 7 (a) Average maximum compressive strength (MPa) required to fracture pellets and (b) average maximum emergence of seedlings from pellets sown in the glasshouse for pellets consisting of three combinations of mineral product ingredients (Bent-DE, Bent-Oil, and DE-Oil) and two extrusion times (0–10 mins and 10–20 mins). Compressive strength was used as a measure of pellet 'hardness'. Error bars represent the standard error of the mean

2.4 Example 4: improving germination and emergence capacity of native seeds through seed priming

Seed priming involves the controlled hydration of seeds to activate the germination process to a point just prior to radicle emergence. Seeds are then dried back and stored for sowing at a later date. Once sown, more uniform germination and synchronised seedling emergence is expected. Seeds can be primed in different solutions such as pure water (hydro-priming) or solutions containing polyethylene glycol (osmo-priming), with each species requiring different solutions and a different duration of priming. Osmo-priming has some advantages over hydro-priming as it allows for more precise control of the seed hydration process, which for fast-germinating Pilbara species (where the radicle can emerge in less than one day) can prevent seeds from prematurely germinating during the priming process.

Following discussions surrounding the priming requirements for native seeds, a prototype priming machine was designed and constructed for use in mine rehabilitation programs (Figure 8). Priming of seeds across a range of osmotic potentials and aeration flow rates has been tested using many Pilbara species covering a range of seed sizes, morphology, and appendages. The six-cylinder priming apparatus is now routinely used for treating seeds in the Pilbara and has the capacity to treat large batches (e.g. 1–2 kg) of pure seeds, of low volume, at any one time.

In some trials using primed seeds of the dominant grass genus of the Pilbara, *Triodia*, hydro-priming has shown potential to improve seedling emergence under field conditions (Erickson et al. 2017; Kildisheva 2019). To achieve this result, batches of freshly collected, dormant seeds of *T. pungens* were cleaned out of the florets and treated with karrikinolide, a smoke-derived germination stimulant, via hydro-priming. Other batches of seeds were hydro-primed and coated with a calcium carbonate seed coat. These seeds were then precision-sown below the soil in field plots constructed within a purpose-built rain-manipulation shelter in the Pilbara (Figure 9). In the field plots that contained topsoil and that received a simulated rainfall regime (via irrigation) of 120 mm over a seven-day period, the highest emergence occurred among hydro-primed seeds sown below the soil surface (approximately 35–40%) and represented a three- to four-fold increase in seedling emergence compared to global averages for field sown seeds in seasonally dry environments (Merritt & Dixon 2011; James et al. 2013; Erickson et al. 2017). As a direct comparison, there was almost no recruitment of unprimed seeds or intact florets sown below the soil due to the strong influence of physiological dormancy constraining germination in freshly collected, untreated material.

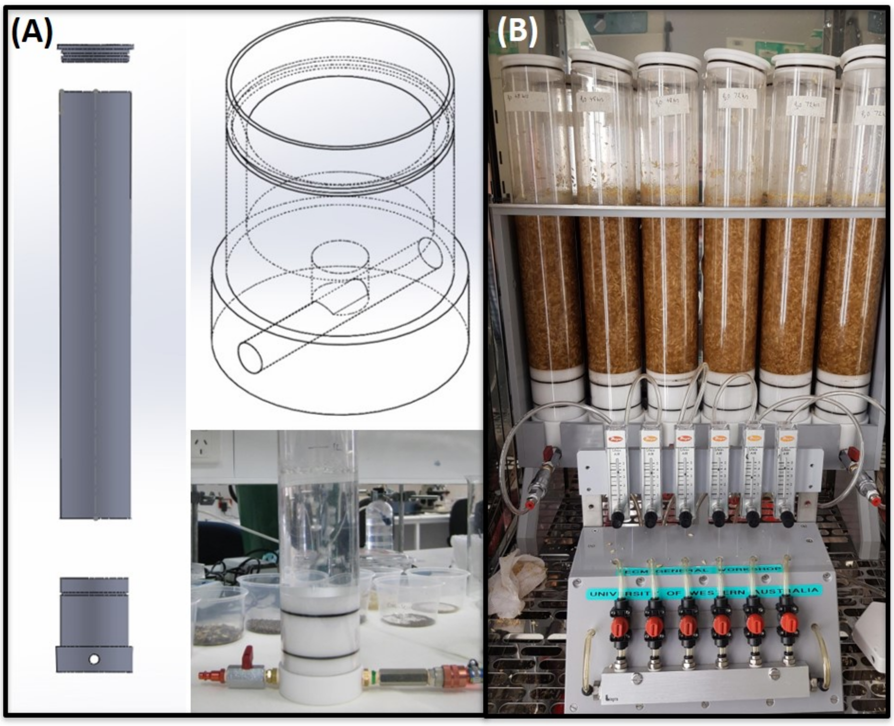

Figure 8 **(a) Features of the priming apparatus; (b) Constructed unit during testing**

Figure 9 **(a) The rain-manipulation shelter located in the Pilbara at Mt Whaleback mine. (b) This facility allows the testing and field-proofing of seed pre-treatments with regards to germination, emergence, and early seedling establishment. (c) Seeds are precision-sown; (d) 3–5 mm below the soil surface and covered with soil after seeding. The facility houses five different reconstructed soil profiles and can test up to four different simulated rainfall regimes in one trial (adapted from Erickson et al. 2017)**

2.5 Example 5: field-testing seed-enhancement technologies in the Pilbara

Seeds of native Pilbara species possess a range of dormancy mechanisms that can limit the potential for plant establishment, even several years following seeding, and the techniques to remove these germination impediments vary widely (Erickson et al. 2016b; Lewandrowski et al. 2017). In addition to developing appropriate seed pre-treatments to overcome seed dormancy and germination impediments, we have conducted field trials that intensively assessed the germination, emergence, and early seedling performance of more than 20 species under a range of simulated rainfall scenarios and soil conditions in the Pilbara. These trials have largely been carried out in the purpose-built rain-manipulation shelter (Figure 9) or in available mining partner rehabilitation sites. One example of a field trial consisted of testing a range of species-specific seed treatments in the rain-manipulation shelter in early 2018. This study applied many years of research into seed biology by combining optimised dormancy-break treatments with seed-enhancement treatments (using the modified or custom-built equipment discussed in Sections 2.2–2.4) to assess the development of a plant community containing 10 species. The simulated rainfall amounts represented events falling over a seven-day period (applied in four events), totalling 120 mm. This kind of rainfall pattern is typically observed after a tropical low-pressure system develops in the Pilbara. Additionally, smaller rainfall events of 15 mm at three and five weeks, and a single 7.5 mm event at nine weeks were simulated after the initial rainfall pulse. The aim of this work was to demonstrate what happens to the plant recruitment potential of seeds when managed under various treatment scenarios (Table 1):

1. No management of seed dormancy.
2. Application of the optimised dormancy-break treatments.
3. Application of further seed-enhancement treatments to 'boost' the recruitment potential.

Table 1 Examples of species tested under a range of varying seed dormancy and enhancement treatments in the rain-manipulation shelter. Increasing levels of treatments were applied to evaluate whether singular treatments or combinations of treatments increase the recruitment potential of seeds

Species	Treatment Level 1	Treatment Level 2	Treatment Level 3
Cymbopogon ambiguus	Not treated	Flash flamed	Flash flamed + polymer seed coat added
Triodia wiseana	Not treated	Cleaned to seeds from florets and hydro-primed in smoke	Cleaned to seeds from florets and hydro-primed in smoke and polymer seed coat added
Triodia pungens	Not treated	Cleaned to seeds from florets and hydro-primed in smoke	Cleaned to seeds from florets and hydro-primed in smoke and polymer seed coat added
Goodenia stobbsiana	Not treated	Seeds hydro-primed in smoke	Seeds hydro-primed in smoke and polymer seed coat added
Ptilotus exaltatus	Not treated	Flash flamed florets	Flamed florets and cleaned to seeds
Acacia ptychophylla	Not treated	Wet heat treated	Wet heat treated and osmo-primed at -1.25 MPa
Acacia tumida	Not treated	Wet heat treated	Wet heat treated and osmo-primed at -1.25 MPa
Gompholobium polyzygum	Not treated	Wet heat treated	Wet heat treated and osmo-primed at -1.25 MPa
Tephrosia densa	Not treated	Wet heat treated	Wet heat treated and osmo-primed at -1.25 MPa
Eucalyptus gamophylla	Not treated	Osmo-primed at -1.25 MPa	Osmo-primed at -1.25 MPa and polymer seed coat added

Maximum survival of seedlings at the six-month monitoring point was highest in plots receiving seeds first treated to alleviate dormancy and then subjected to a seed-enhancement treatment (i.e. 11% overall seedling survival; double-tick green zone, Figure 10). Of the 350 seeds sown per square metre, average seedling density for these best performing plots was 43 seedlings/m^2. Such a density is comparable to observed natural recruitment events of *Triodia* grasslands after fire (Burbridge 1943). Perennial grasses comprised approximately 70% of this final density of all species sown (i.e. proportionately 51% grasses, 13% herbs, 27% shrubs, and 9% trees), and on average there was 22% survival of the sown grass seeds. Of the 10 species seeded, six were still growing at the time of the last (six-month) monitoring period. In comparison, for seeds treated for dormancy only (single-tick green zone) and for seeds not treated for dormancy at all (red cross zone), six-month survival equated to 4.4 and 2%, respectively. Seedling density for these plots ranged between six and 23 seedlings/m^2.

These findings highlight the benefits to rehabilitation performance that can be achieved through the use of seed-enhancement technologies and by addressing multiple elements of the chain-of-seed-use (i.e. the seed management cycle in Figure 1), which deliver positive changes to seeding practices within mine rehabilitation programs.

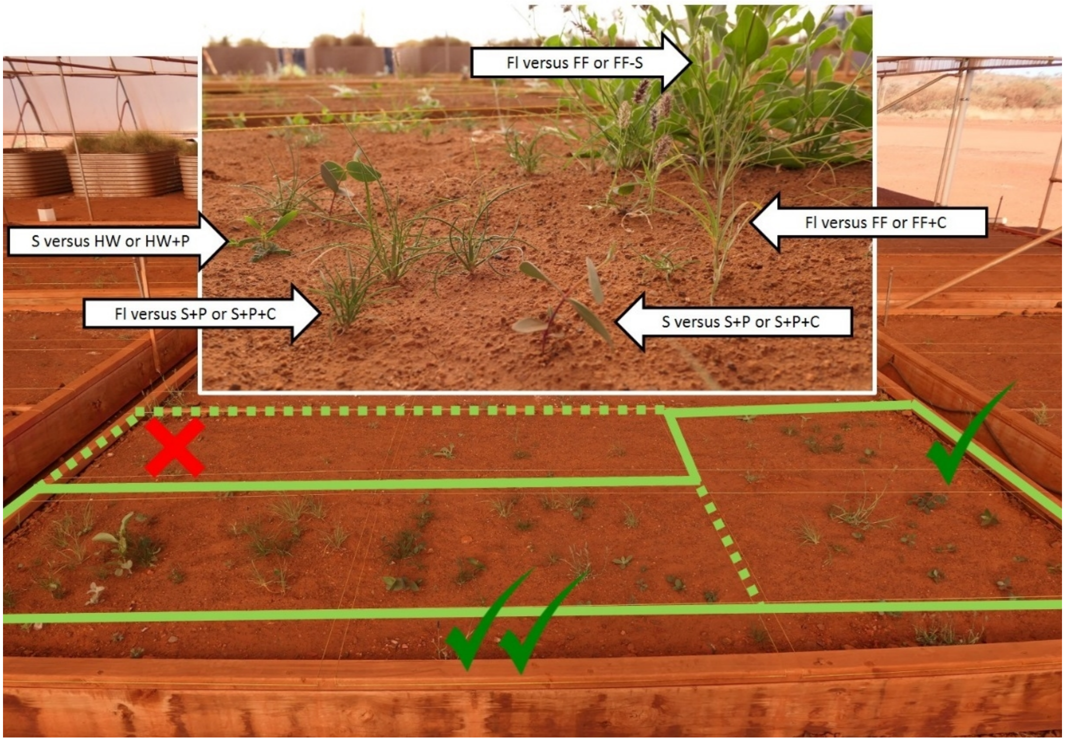

Figure 10 A visual example of seedling establishment in a recent trial that compared various seed dormancy and enhancement technology treatments. The plots that received untreated seeds (red cross zone; average final density of 7.5 seedlings/m^2 after six months) did not respond to the simulated rainfall conditions delivered in this trial (i.e. 120 mm over a seven-day period – four events of 30 mm, followed by a single 15 mm event at three and five weeks, and a single 7.5 mm event at nine weeks, after the first initial rain). In comparison, the plots that received seeds treated for dormancy (single-tick green zone; average final density of 13.5 seedlings/m^2) and seeds treated for dormancy with an additional seed-enhancement treatment (double-tick green zone; average final density of 43 seedlings/m^2) had considerably more seedlings establish. Depending on the species individual florets/seeds were treated differently to manage the recruitment potential on a species-by-species basis (white inset: FI = florets, S = seeds, FF = flash flamed, FF-S = flash flamed + cleaned to seeds, FF-C = flash flamed + coated, HW = hot-water treated, HW+P = hot-water treated + primed, S+P = seeds + primed, S+P+C = seeds+primed+coated)

3 Conclusion

As more seed-based information has been developed for Pilbara rehabilitation programs, practitioners have progressively implemented more of the critical steps required for efficient seed-use (i.e. the seed management cycle in Figure 1). There has been a conscious effort to improve seed collection at scale, store seeds under controlled conditions, understand and apply seed pre-treatments, and further comprehend the regeneration biology of many species (see examples and discussions of improved seed-use in Erickson et al. 2016a, Muñoz-Rojas et al. 2016b; Lewandrowski et al. 2017; Shackelford et al. 2018). However, to date, it could be argued that accurate seeding rates and seed placement in the field (i.e. the eco-engineering focus and transitional grey arrows in Figure 1) are not yet carried out with the precision required to ensure that all of the preceding efforts of seed procurement, cleaning, storage, and pre-treating do not go to waste.

To successfully achieve rehabilitation of a diverse range of Pilbara plant species and a similar community structure to the pre-disturbed environment, research in the following areas continue to:

- Advance the application of flash flaming as a technology to remove unwanted seed appendages to a wider range of species.
- Combine the optimised flash flaming treatments with additional seed-enhancement technologies (priming, pelleting, and coating).
- Critically evaluate the limitations of current mechanised seeding techniques used in rehabilitation (e.g. mining operations) and large-scale cropping to guide engineering modifications or new designs to improve precision delivery of native seeds in adverse rocky, uneven, and sloped landforms.
- Design, construct, and test prototype direct seeding machines that can accommodate and efficiently deliver a wide range of seeds that differ in shape, size, and weight at the scale required.

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