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From angles to amendments: learnings from field trials to improve rehabilitation practices

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Abstract

Rio Tinto strives to deliver quality rehabilitation outcomes across its mining operations in the Pilbara, Western Australia. Successful rehabilitation of the Pilbara is challenging due to factors including variable rainfall, high temperatures, poor growth medium quality and challenges with returning native species*. Therefore, to inform evidence-based rehabilitation practices, Rio Tinto established a suite of field trials. Here we discuss 3 trials that demonstrate both the breadth of current research and the complexity of conducting successful rehabilitation in the Pilbara. The first trial relates to the seeding rates and timing necessary to promote diverse vegetation communities. For this trial we found low plant densities where seed was not applied but high variation in the different seed rates. The effect of seasons was unable to be determined due to differences in seeding methodologies. These findings allow for more targeted seed rates and investigations into seeding methodologies. The second trial tested different amendment types and watering regimes for tubestock of Eucalyptus leucophloia, an iconic tree species that has low establishment from seed in rehabilitation. We found that water at the time of planting substantially increased survival and no consistent effect of amendments, with these findings important for future planting techniques. The third trial investigates slope angle effects on vegetation establishment. Here we tested the effect of irrigation and slope angles at 16, 18 and 20° on vegetation establishment. So far there appears little effect from slope angle but a strong effect of irrigation on perennial densities. Collectively these trials highlight the critical role of field-based evidence in shaping effective rehabilitation prescriptions and improving long-term outcomes, with findings applicable to rehabilitation in the Pilbara more broadly.*

Keywords: *Pilbara, field trials, seed rates, seed timing, tubestock, landform design*

1 Introduction

Rio Tinto operates 18 iron ore mines with associated port and rail facilities in the Pilbara region of Western Australia. Operating conditions require areas disturbed by mining to be progressively rehabilitated to the desired post-mining land use. To meet these obligations Rio Tinto has been conducting rehabilitation for decades, and since 2019 there has been a substantial increase in the amount of area rehabilitated each year. Building on years of rehabilitation execution, outcomes have varied across landform types and seasons; therefore, strengthening consistency is a current focus and supported by expanded monitoring and targeted field trials. Ensuring quality rehabilitation will promote desirable biodiversity values in the Pilbara and meet the expectations of stakeholders (Wittkuhn et al. 2026).

Rio Tinto aims to rehabilitate areas to a native ecosystem similar to the dominant ecosystem surrounding the area prior to mining. This often results in a vegetation community dominated by *Triodia* (spinifex) grasses, scattered with shrubs such as *Acacias* and herbaceous species, and occasional trees of *Eucalyptus* species. Rehabilitation occurs on a range of different landform types of varying complexity across Rio Tinto's Pilbara operations, with more complex landforms often more challenging to successfully rehabilitate due to landform design requirements such as steep slopes, which may influence water dynamics. Depending on the landform

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and its specific requirements, typically rehabilitation activities include reshaping of the landform to the design specifications, applying growth media [typically topsoil, subsoil or alternative growth medium (AGM)], ripping the landform and seeding with native plant species from the region, followed by ongoing monitoring.

The Pilbara is a harsh environment in a semi-arid region where rainfall is typically a limiting factor to successful rehabilitation (Shackelford et al. 2017; Lewandrowski et al. 2021). The majority of rainfall typically falls between December and March (i.e. the wet season). Yearly rainfall averages across the Pilbara differ among regions but can range from 288 to 309 mm per year (Rio Tinto's Pilbara mine site weather stations). However, most of the rainfall is driven by tropical cyclones, with average long-term total rainfall from December to March of approximately ~180mm, but it ranges from 0–~700 mm, highlighting the substantial variability and unpredictability of rainfall events (Bureau of Meteorology 2026). Temperatures throughout the year are warm, with long-term (1997 to 2025) maximum temperatures peaking at approximately 42.7°C and 44.3°C in January (warmest month), and at 25.3°C and 23.8°C in July (coolest month) at Newman (climate station 7176) and Paraburdoo (climate station 7185), respectively (Bureau of Meteorology 2026). These conditions, and site attributes including growth media with a lack of nutrients and poor water-holding capacity, are often unfavourable for germination and establishment (Muñoz-Rojas et al. 2016; Lewandrowski et al. 2021; Erickson et al. 2023). Additionally, the Pilbara is composed of diverse vegetation communities but has complex seed traits including dormancy and longevity (Erickson et al. 2016a; Erickson et al. 2017; Dalziell et al. 2022; Wood et al. 2026), and poor knowledge of species ecologies and their drivers of establishment success (Wood et al. 2026) further amplify challenges associated with completing successful rehabilitation in the region.

Rehabilitation methods, including landform design and seeding prescriptions, have evolved over time and there is an ongoing need to strengthen the site-specific evidence base and prescriptions. To inform prescriptions, Rio Tinto has set up a range of onsite trials in the Pilbara to understand how different factors may influence rehabilitation success. Here we explore the effects on vegetation outcomes from 3 trials in progress by Rio Tinto: (1) impact of seed rates and timing of delivery, (2) amendments to promote the survival of *Eucalyptus leucophloia* Brooker (snappy gum) tubestock, and (3) investigations on the impact of slope angle and irrigation. Despite these trials being early in their establishment phase, learnings have already been gained and the importance of replicated trials to inform practices is highlighted.

2 Testing of seed rates and timing of seed delivery to inform seeding prescriptions

Utilisation of fresh topsoil in the Pilbara is a challenge. Topography, large disturbance areas and long mine lives mean topsoil management must balance availability, logistics and scheduling integration in mine plans, even when topsoil is applied. Thus, across higher disturbance landforms such as waste dumps and borrow pits, seed is broadcast into the rehabilitation at a single point in time following landform reshaping. This is the last phase of the rehabilitation process and generally the species seeded will form the bulk of the future perennial vegetation community.

Historically, an industry standard of ~8 kg/ha of seed was used across Pilbara rehabilitation projects. Typically, this rate did not consider seed quality, particularly the seed weight, purity and viability, or the expected survival rate for each species, so rehabilitation often did not meet required plant densities targets. Rio Tinto has developed targets specifying minimum plant densities that should be present in early rehabilitation to maximise meeting rehabilitation cover targets in mature rehabilitation. Therefore, utilisation of a seeding rate based on seed quality and realistic survivability rates, as detailed in the Florabank Guidelines (Commander 2021), was trialled.

Additionally, in the Pilbara, conducting seeding activities as close as possible to expected rainfall (i.e. the wet season) is generally considered best practice. This approach is favoured as it minimises the time between seed deposition and rainfall, where seed loss could occur due to processes including predation, dispersal or loss of viability in pre-treated seed. Due to increasingly larger areas being rehabilitated by Rio Tinto, it may become logistically challenging to complete all seeding of rehabilitation areas just prior to the wet season.

Therefore, this trial also tested the effect of seed timing by comparing seeding in the dry season against seeding just prior to the wet season (normal practice).

The aims of this trial were to test knowledge gaps associated with seed rate and seed timing. It was expected that seed mixes which incorporated seed quality factors and realistic survivability would have higher rates of recruitment than the standard 8 kg/ha seeding rate. In addition, it was expected that seed mixes sown in the wet season would have higher plant densities than seed mixes sown in the dry season, due to less time between seeding and rain.

2.1 Methods

2.1.1 Trial design

To quantify the effect of seed delivery timing and seeding rate, this trial tested seed delivery seasons. The wet season sowing occurred in December 2023 and was characterised by hot temperatures and cyclonic rainfall events which typically occur in February to March, while the dry season seeding occurred in July 2024 and typically had no rainfall and milder temperatures.

The second factor tested was seeding rate. (Table 1) Two seeding rates were tested, with the ~28 kg/ha rate reflecting the adjusted seed rate. The adjusted seeding rate was determined using the Florabank Guidelines and involved: (1) determining the target stem density for different species/lifeforms, (2) dividing this by expected species survivability to create a target seed density, and (3) incorporating the pure live seed weight to determine the weight of each seed batch per species for broadcasting into rehabilitation (Commander 2021).

To quantify the effect of applying seed, a pure control treatment was included where no ripping or seed were applied. In addition, for each timing a control treatment was included where the ground was only ripped (without seed applied). All treatments were ripped, except for the not ripped, not sown control (treatment number 1, Table 1). All combinations of the timing and seed rate levels were included, which resulted in 7 treatments; each replicated 3 times (Table 1).

Table 1 Treatments in the seeding rates and timing trial

Treatment number	Treatment	Treatment number	Treatment
1	Not sown or ripped	2	December sowing, No Seed
3	July sowing, No Seed	4	December sowing, 8 kg/ha
5	July sowing, 8 kg /ha	6	December sowing, ~28kg/ha
7	July sowing, ~28kg/ha		

2.1.2 Trial installation

The 21 replicates (3 replicates per treatment) were randomly assigned across 2 batters of a waste dump at the Channar mine site, approximately 15 km southeast of Paraburdoo. Substrate was of mine waste overlain with locally sourced stockpiled topsoil and subsoil to a depth of 200 mm. Replicates were seeded along the contour of the batters. In December 2023 seeding was implemented using a dozer-mounted drum seeder, with the area ripped to a ~150 mm depth, and ripping and seeding occurred in a single pass. For the July 2024 (dry season) sowing event and after ripping, a drone was used to seed the area to reduce exposure of personnel and equipment on steep batters. While the seed delivery method differed, both seed delivery events used the same ripper and depth. A weather station was installed during the December 2023 seeding to track rainfall and temperature across the trial site.

Approximately 62% of the total seed weight was composed of *Triodia,* with 6% composed of *Acacia* species. For both seed delivery times, seed baches and species composition were consistent, with best practice dormancy-breaking techniques for each species used, typically following Erickson et al. (2016a). All seeds were tested for purity and viability to inform the percentage and weight of pure live seed. The per cent of pure live seed ranged from 13–100% for all species, and was between 33–72% for *Triodia*, and > 80% for 13 of the 14 *Acacia* species, with the remaining *Acacia* at 61%.

2.1.3 Trial monitoring

Within each replicate a 100 m long transect was installed, with 2 × 2 m (4 m^2) quadrats placed every 5 metres along the transect. In these quadrats, all plants were counted to genus level where possible or classed as alive or dead monocotyledons (excluding *Triodia*), dicotyledons or weeds. Since December 2023, 5 monitoring events have occurred, with the following results referring to monitoring in March 2026, approximately 1.5 years after the dry season seeding. Throughout this paper, graphs are visualised with 95% confidence intervals (CI) to highlight variance and uncertainty around the mean and reflect likely statistically significant differences at $P < 0.05$ (where confidence intervals do not overlap; Ramsey & Schafer 2002).

2.2 Results and discussion for seed timing and rate trial

Rainfall one month post seed sowing differed substantially among the seasons, with ~4 mm occurring after the wet season sowing and ~13 mm after the dry season sowing. During the first 3 months following sowing, more rainfall occurred after the dry season sowing than the wet season sowing (94 versus 79 mm, respectively).

Approximately 1.5 years following the dry season sowing event in July 2024, the plots without seed or ripping had very few native perennial and *Triodia* plants established for both sowing events (Figures 1a and c). This is likely due to the use of stockpiled topsoil, where seedbank viability typically declines with storage time (Golos et al. 2016).

For the treatment where no seed was applied but ripping occurred, low densities of both native perennials and *Triodia* were observed for both seasons. This may be due to slight drift of seed from other treatments, ripping creating microclimates with more access to water and light, or ripping possibly releasing a chemical that can trigger germination of a range of Australian species in a way similar to smoke (Merritt et al. 2006; Daws et al. 2014). More plants were observed where 8 and ~28kg/ha of seed was applied than the control treatments, with the average perennial density and *Triodia* density of the 8kg/ha July sowing, and ~28kg/ha December and July sowing close to or exceeding the early-stage rehabilitation targets (Figures 1a and c), emphasising the need for seed rehabilitation to meet early-stage rehabilitation targets.

For the seed rates applied and both seasons there was large variation for both perennial and *Triodia* density as depicted through the large CI error bars (Figures 1a and c). This suggests there is not a strong impact of higher seed rates on densities after approximately 1.5 years from the July sowing or just over 2 years for the December sowing. While this trend is unexpected, it may be due to low replication and/or high in-field variability as well as possible seed migration into other plots due to their close proximity. The top part of the batter also had more seed than lower parts of batter, possibly due to uneven metering and deposition of the seed using the dozer.

Species richness and composition from the 2 sowing times differed substantially, with *Triodia* the only native perennial species present in the July sowing after ~1.5 years. Due to differences in timing and seed delivery it is difficult to ascertain the reason for this, but different optimal seed depths among the species was a likely influence. Drones typically place seeds on the soil surface with little burial, thereby likely placing larger seed species at the incorrect depth, which possibly explains the high *Triodia* counts but an absence of any other species. Approximately 59% of the individual plants in the December sowing event were *Triodia* and 41%, *Acacia.* Additionally, species richness was higher here also, with 6 *Acacias* and *Triodia* present across the 8 and 28kg/ha seed rates in the December sowing, respectively, while only *Triodia* was present in the July sowing.

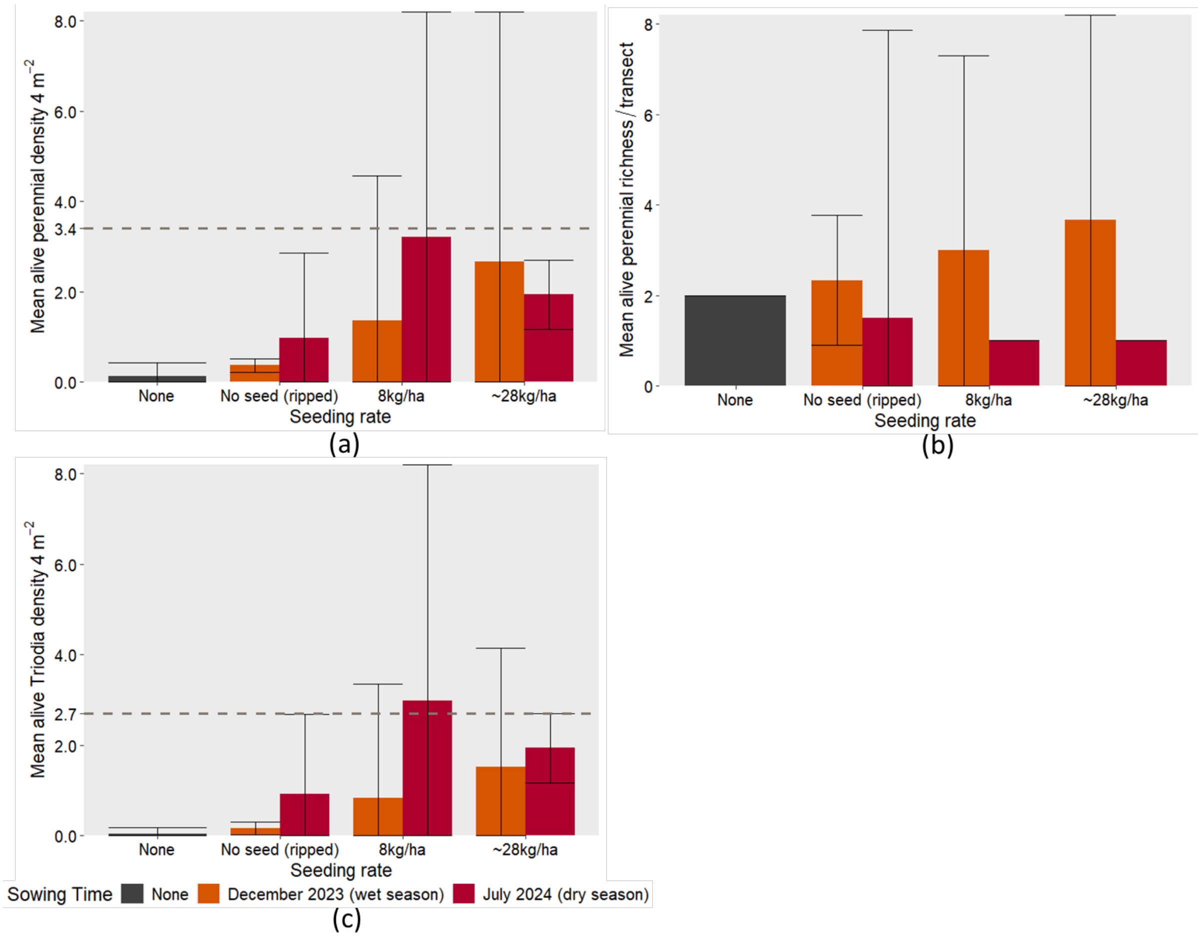


Figure 1 Mean ± 95% confidence intervals for: (a) Native alive perennial density; (b) Native alive perennial richness; (c) Alive *Triodia* density in March 2026, approximately 1.5 years post dry season seeding in July 2024 for the seeding rate and timing trial. The legend in Figure (c) matches all panels, with the dashed grey line reflecting early rehabilitation targets

Given the different delivery methods between seasons, the specific effect of timing could not be isolated. Lack of rainfall in the wet season likely reduced plant germination and/or establishment, as average long-term rainfall combined for January to March is ~180 mm (Bureau of Meteorology). However, differences in perennial composition between the delivery times is of interest and allows for further consideration of the best methods of seed delivery for different species. Across past rehabilitation, areas seeded using a dozer often had a range of perennial species such as *Acacia* and *Senna*, as was found in the December-seeded plots of this trial but not in the July-seeded plots.

3 Amendments to promote survival of *Eucalyptus leucophloia* tubestock

Eucalyptus leucophloia (commonly referred to as snappy gum) is an iconic tree species in the Pilbara. Rio Tinto typically includes seeds of *Eucalyptus leucophloia* in rehabilitation seed mixes, but it has limited establishment in rehabilitation. It is also a culturally important species for many traditional owner groups in the Pilbara. To return this species in rehabilitation, Rio Tinto investigated its survival from tubestock planting. This trial aimed to establish a scalable method of tubestock planting and understand planting prescriptions to maximise survival.

3.1 Methods

3.1.1 Trial design

Limited rainfall and the poor water-holding capacity of soils in the Pilbara likely influence vegetation germination, survival and/or establishment in rehabilitation. To try and improve moisture availability and water-holding capacity around the *Eucalyptus leucophloia* tubestock planted, 3 factors were tested: (1) soil amendments, (2) watering of tubestock when planted and (3) season of planting. Soil amendments may improve plant establishment and/or survival, so commercially available amendments aimed to enhance water-holding capacity were selected. Additionally, previous trials found increased survival of *Eucalyptus leucophloia* tubestock when planted with hand-made Agar bricks . However, the creation of the agar bricks was found to be labour and time-intensive, so TerraCottem arbor was used as a commercially available substitute, as it contains components that promote water absorption (water crystals), as well as fertiliser to stimulate plant growth (Terracottem 2026). This was applied at 40 g per plant, as per TerraCottem's recommendation (Straume pers. comm. 2023). The second amendment used was Seasol Earthcare planting gel, which slowly releases water and nutrients after planting, aiming to stimulate root growth and reduce transplant shock (Arborgreen 2026). This was applied at 20g per plant; the suggested rate for 140 mm plants.

The second factor tested was watering tubestock when planted, as this additional water was expected to provide sufficient soil moisture for plants to establish. Plants were either planted without water or watered in after planting with 4 litres per plant. Based on the planting experience of the team it was estimated that 4 litres of water was needed to saturate the immediate soil zone around the tubestock without causing significant run-off.

The third factor tested was season of planting, with tubestock planted in either July 2024 (dry season with little rainfall and long-term maximum temperatures of around 25°C) or February 2025 (wet season where most rainfall occurs but temperatures frequently exceed 40°C; Bureau of Meteorology 2026). Substantial differences in temperatures and rainfall likely influence plant establishment.

Combining each level of these 3 factors resulted in 12 treatment combinations (Table 2). Each treatment combination was replicated with 40 plants in a completely randomised block design. In both August 2024 (dry season) and February 2025 (wet season), 240 plants were planted across 6 treatments, with a total of 480 plants installed for the trial

Table 2 Treatments in the *Eucalyptus leucophloia* tubestock trial

Treatment number	Treatment	Treatment number	Treatment
1	No amendment, no watering in, winter plant	2	No amendment, no watering in, summer plant
3	No amendment, watering in, winter plant	4	No amendment, watering in, summer plant
5	TerraCottem, watering in, winter plant	6	TerraCottem, watering in, summer plant
7	TerraCottem, no watering in, winter plant	8	TerraCottem, no watering in, summer plant
9	Seasol gel, watering in, winter plant	10	Seasol gel, watering in, summer plant
11	Seasol gel, no watering in, winter plant	12	Seasol gel, no watering in, summer plant

3.1.2 Trial installation

The tubestock trial was established on a flat area of a waste dump at Rio Tinto's West Angelas mine site, approximately 100 km west of Newman. The area used for planting formed part of a larger rehabilitation project completed late 2024, with substrate composed of mine waste overlain with locally stockpiled topsoil to a depth of 200 mm. A plant was consistently spaced every 5 m. For each planting season the tubestock was prepared approximately 6 months prior at a nursery located in Perth, using seed from the relevant provenance. To adjust to the Pilbara conditions, the tubestock was hardened for a month prior to planting under full sun conditions in the Pilbara, with daily watering. Prior to planting, dead or diseased plants were removed.

Planting holes were made using a battery-powered auger with a 200 mm auger bit. Holes were dug until they hit the waste rock underneath the topsoil, which occurred at approximately 100 mm deep. Each amendment was applied close to the root ball (Seasol gel) or mixed into the planting hole (TerraCottem arbor). After each replicate block of plants were installed, 4 litres of water was applied to each of the plants receiving the watering-in treatment.

3.1.3 Trial monitoring

The planted tubestock was initially monitored approximately 3 months after each planting time and then periodically thereafter to capture changes with the seasons. For each tubestock planted, survival was assessed through determining if the plant was alive or dead. Height was also recorded to the tallest apical bud from the pre-installed survey marker. Each plant was also assigned a qualitative health score as follows: 0 = plant dead, 1 = plant dying and/or highly stressed, 2 = plant slightly stressed (in average condition, not actively growing) or 3 = plant healthy (actively growing).

3.2 Results and discussion for *Eucalyptus leucopholia* tubestock planting

In the first ~2.5–3.5 months following planting, the survival of *Eucalyptus leucopholia* tubestock substantially decreased in all treatments for both the wet and dry season plantings, then remained largely unchanged (Figures 2 and 3). This suggested that the bottleneck to establishment is < 3.5 months, regardless of the time of year the planting occurred. Through more frequent early monitoring after planting, specific bottleneck time frames could be determined. However, additional monitoring of the seedlings, particularly through multiple wet seasons, is required to confirm long-term persistence.

For the dry season plantings that occurred in August 2024, survival after 13 months was highest for watered-in plants (Figure 2). The survival of the tubestock watered in at planting was lowest for the plants without amendment (17.5% survival) and highest for those with TerraCottem and Seasol gel added at planting (27.5 and 22.5% survival, respectively; Figure 2). For those not watered in, survival ranged between 0 and 2.5% (Figure 2). This highlights the need for applying water at planting to promote survival. Following planting, rain did not occur until 12 September (just over one month after planting) with only 0.06 mm recorded. Approximately 82 mm of rainfall was recorded between planting and the first monitoring event in October, with the majority occurring roughly 6 weeks post planting.

At approximately 7 months post wet season planting, survival for both the Seasol gel and TerraCottem tubestock was similar regardless of whether or not the plants were watered in at planting, but for tubestock without amendments, survival differed between the watering regimes (Figure 3). This is likely due to approximately 28 mm of rainfall occurring during the planting window, which would have improved soil moisture, possibly rendering the amendments redundant. This may be due to the water-holding components of the amendments exceeding their capacity, or simply that water was more important for survival than any sort of amendment. Between the time of planting in February 2025 and the first measurements in April 2025, approximately 72 mm of rainfall occurred, which was a similar volume of water received in the 6 weeks after the dry season planting. However, the timing of this rainfall was different between the two plantings, with some rainfall received during planting in the wet season, with rainfall received over a month after planting in the dry season.

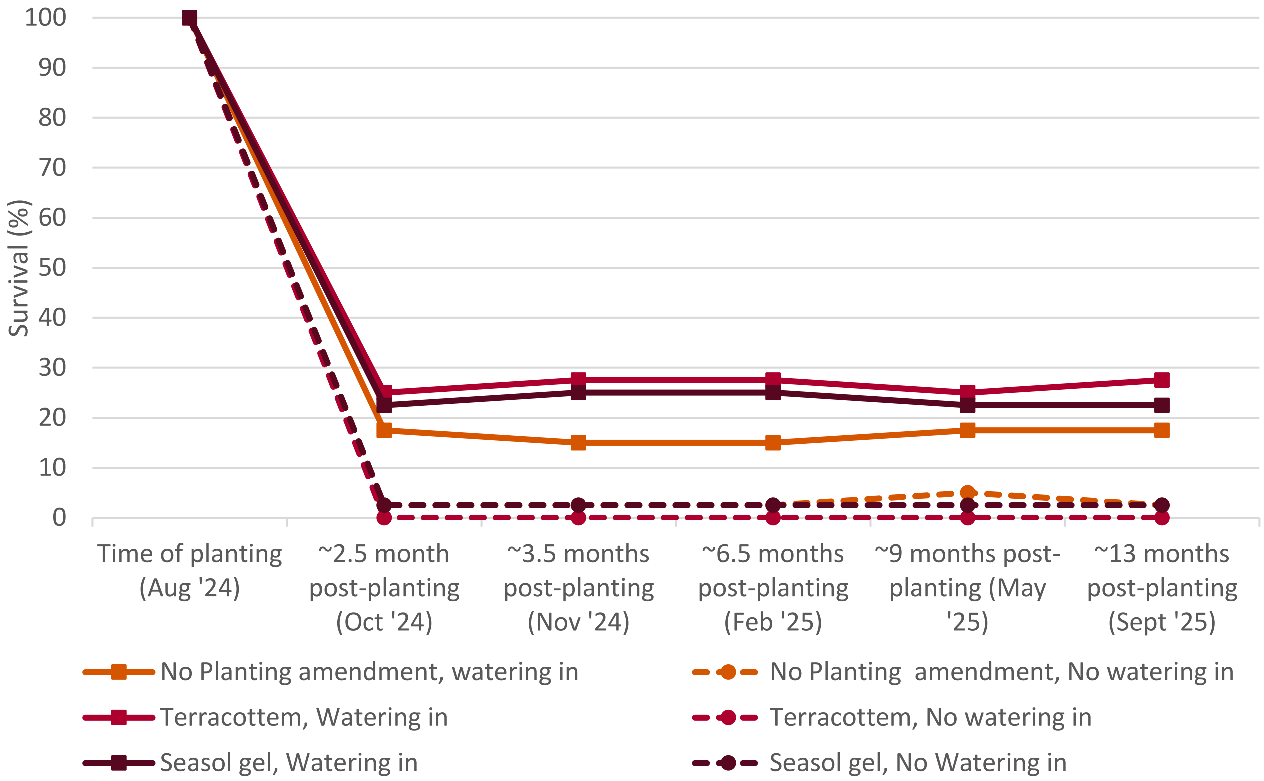


Figure 2 Survival of *Eucalyptus leucopholia* tubestock planted in the dry season

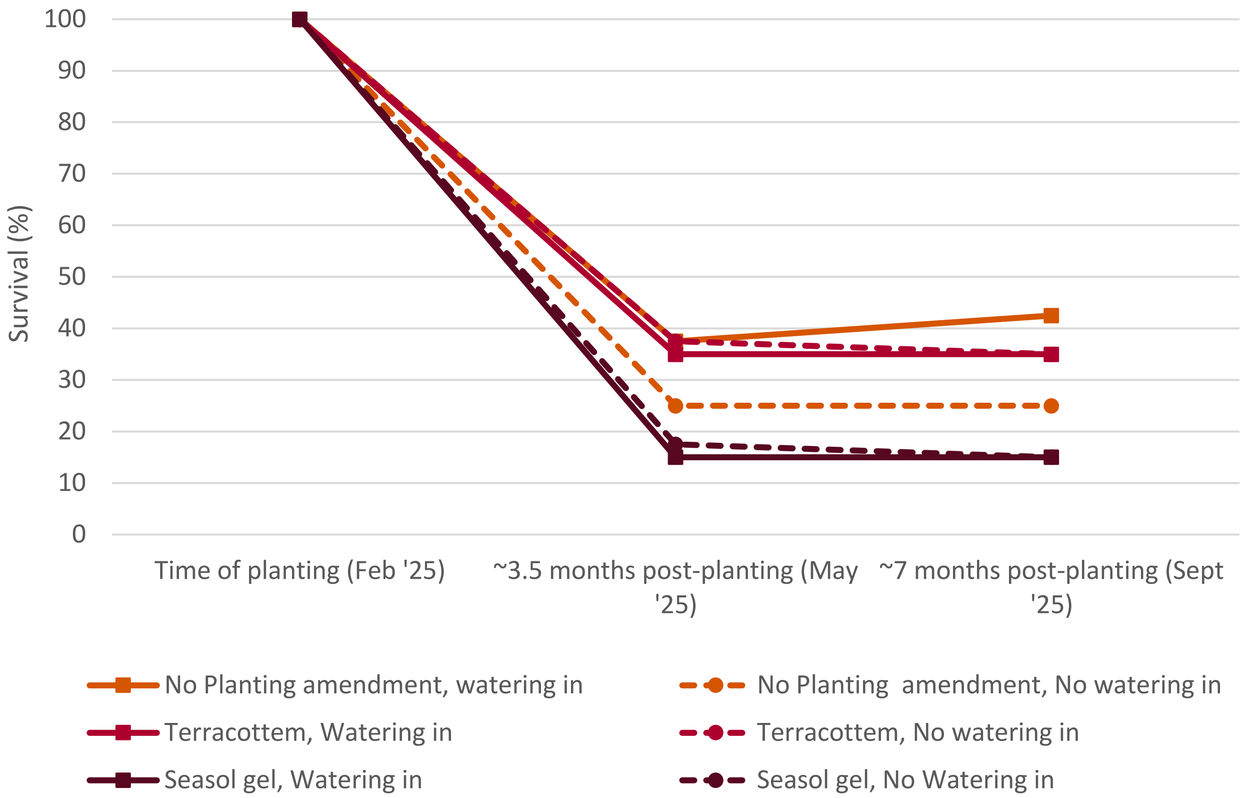


Figure 3 Survival of *Eucalyptus leucopholia* tubestock planted in the wet season

At a time of similar plant age post planting (~6.5 months for dry season planting and approximately 7 months for the wet season planting), the best performing tubestock treatments differed (Figures 2 and 3). The dry season planted tubestock watered in with Seasol or TerraCottem had the highest survival rate; between 25 and 27.5% survival, respectively (Figures 2 and 3). This is approximately 15% lower than tubestock that was watered in without amendment (the best performing treatment in the wet season planting), which also received 28 mm of rainfall at planting.

In another Pilbara mining operation trial, *Eucalyptus leucopholia* seedlings were planted in January 2024 and watered under simulated pulse rainfall conditions until end of May 2024 (Standish et al. 2025). Two months following these watering events (approximately 6 to 7 months after planting), 33% of seedlings had survived (Standish et al. 2025), which is slightly lower than the survival rates achieved in this trial; watered-in tubestock without amendments planted in summer achieved 42.5% survival. Differences in survival rates could be due to a range of factors such as planting conditions and sites, watering regime and seedling quality, but this work highlights the applicability of tubestock in rehabilitation areas.

These results highlight the importance of watering in at the time of planting for *Eucalyptus leucophloia* tubestock. Survival of the wet season plantings was high, likely due to the high amounts of rainfall received. However, the difference between no watering in and watering in for tubestock without amendment was substantial, suggesting that watering is critical. Due to very poor survival of the dry season plantings without watering, it also highlights the importance of water. No single amendment or treatment performed best across both seasons, which could also be in part due to differences in the rainfall amounts received at planting as well as other factors like tubestock quality, growing climate and/or hardening off climates. Additionally, it would be interesting to trial the survival of tubestock planted in the wet season without a large rainfall event at the time of planting, and if this is comparable to dry season planting, given that there would be larger evapotranspiration rates expected during the wet season. To determine the effects of the planting season and amendments, further monitoring of the tubestock is required; particularly over multiple dry seasons, as this is when mortality is likely to occur. Broadly speaking, these results highlight that planting of tubestock in rehabilitation is a viable strategy for plants required at lower densities but watering at the time of planting is required.

4 Slope angle trial

Pilbara waste landforms are designed considering a range of factors including spatial footprint, material types, topography, climate and erosion potential, with the final landform needing to be stable over the long term (Howard & Loch 2019). Based on these parameters, design requirements will change; one of these being the angle of the slopes. To support reduction in the disturbance footprint and increase operational efficiencies, select waste dumps with low erodible material types utilise 20° slopes. However, the differences in water run-off and penetrability between slope angles, and their impacts on vegetation performance, are largely unknown. Therefore, a trial was implemented to see if vegetation development varies across a range of slope angles.

4.1 Methods

4.1.1 Trial design

To understand if vegetation development differed across slope angles, this trial tested 2 factors. The first was slope angle, with slope angles of 16, 18 and 20° tested, based on previous observations that plant growth on rehabilitated waste dumps was greater on flat areas than on sloped batters. The second factor tested was irrigation, with areas of each slope angle irrigated and not irrigated (the control). Irrigation was completed due to the strong link between the recruitment of *Triodia* and sufficient water at the germination and emergence stages (e.g. Lewandrowski et al. 2016; Erickson et al. 2023).

Each slope angle was assessed against each irrigation treatment (irrigation or no irrigation), resulting in 6 treatments (Table 3). The 3 slope angles were replicated 3 times across 3 batters on a waste dump. Three irrigated and non-irrigated plots were nested within each slope angle replicate, for a total of 27 irrigated and 27 non-irrigated plots.

Table 3 Treatments in the slope angle trial

Treatment number	Treatment	Treatment number	Treatment
1	20° without irrigation	2	20° with irrigation
3	18° without irrigation	4	18° with irrigation
5	16° without irrigation	6	16° with irrigation

4.1.2 Trial installation

The trial was located at a waste dump at the Channar mine site, approximately 20 km southeast of Paraburdoo. In 2024 the trial landform was reprofiled with the required slope angles. A 200mm depth of alternative growth medium (AGM) was applied and a seed mix of native plants at a rate of 14.1 kg/ha was applied in December 2024. The seed mix composition and pre-treatment were consistent across all treatments. Seed was deployed using a drone, with seed covering harrows towed by a bulldozer passed over the area immediately after seeding.

Three 9 × 9-m irrigation plots were installed in each slope angle plot, with unirrigated plots spaced between. Water was applied using pressure-compensated sprinklers from 6 to 12 February 2025. The design installed aimed to apply20 mm daily to each of the irrigated plots for 7 days, totalling 140 mm. These water rates were chosen as *Triodia* recruitment has been found to increase when 120 mm of water is applied over one week (Erickson et al. 2023). In practice, plots received approximately 20 to 30 mm daily, with plots on lower batters receiving more water than those on higher batters due to the influence of gravity draining the irrigation system. Locally sourced groundwater was applied and recorded an electrical conductivity reading of 1.5 to 1.7 dS/m at 23 °C, which is considered slightly saline. Prior to irrigation, EC-5 soil moisture probes (Meter group) were installed 20, 150 and 250 mm below the surface in all plots with data logged to a ZL6 datalogger (Meter group). A weather station was installed at the trial site to record local rainfall (ATMOS 41, Meter group).

4.1.3 Trial monitoring

In March 2025, approximately one month following irrigation of the trial area and 3 months after seeding, a 4 × 4 m fixed monitoring quadrat was installed at each replicate in the centre of each irrigated and non-irrigated plot. Alive and dead plant counts within the quadrat were recorded, with count of individuals to species level where identification was possible, or to life form if the species couldn't be identified. Following this initial monitoring, subsequent monitoring occurred in June and October 2025, and in March 2026.

4.2 Results and discussion for slope angle trial

After seeding in December, but prior to irrigation in February, approximately 70 mm of rainfall occurred, with 20 mm of this occurring during seeding operations. While rainfall does typically occur during December to March in the Pilbara, the observed rainfall does not occur consistently each year. The high amount of rainfall so close to seeding likely encouraged germination, emergence and/or establishment of some species, so it is important to note that the non-irrigated plots still received rainfall. However, the rainfall received was less than 120 mm. A rainfall amount greater than 120 mm received in a week is considered ideal for *Triodia* recruitment (Erickson et al. 2023).

At the time of the most recent monitoring event in March 2026, approximately 13 months following irrigation and 15 months post seeding, 97% of all perennial plants observed were *Triodia*. For *Triodia* plants, high variability was observed across all replicates for all treatments, with the high counts in the irrigated 18° slopes largely from a single batter (Figure 4). This high variation means that a clear effect of slope angle and irrigation on early plant densities cannot be determined. Additionally, this was the only treatment where the average density exceeded the early-stage rehabilitation target of 2.7 *Triodia* plants per 4 m^2 (Figure 4). Typically, though, there were more *Triodia* plants in the irrigated plots, as expected.

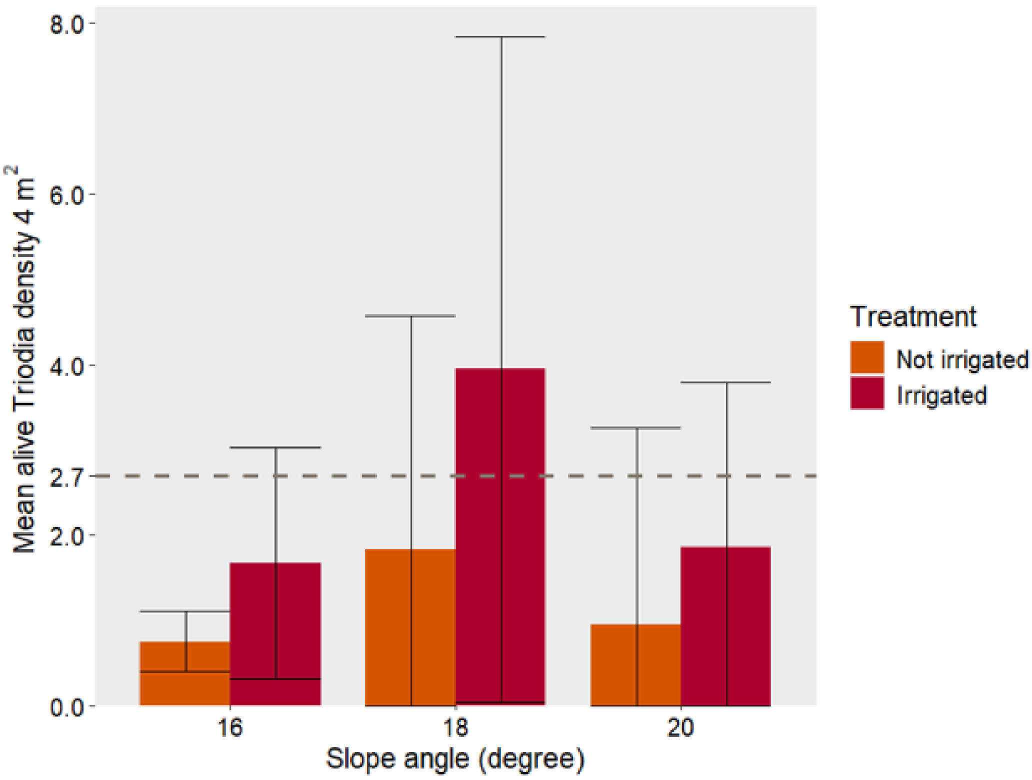
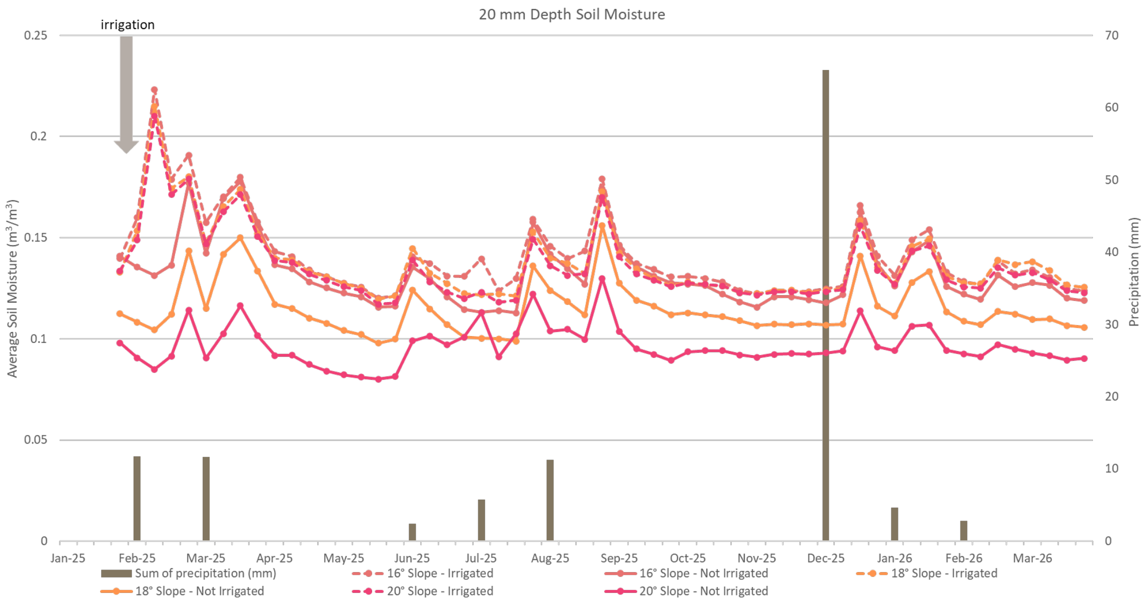
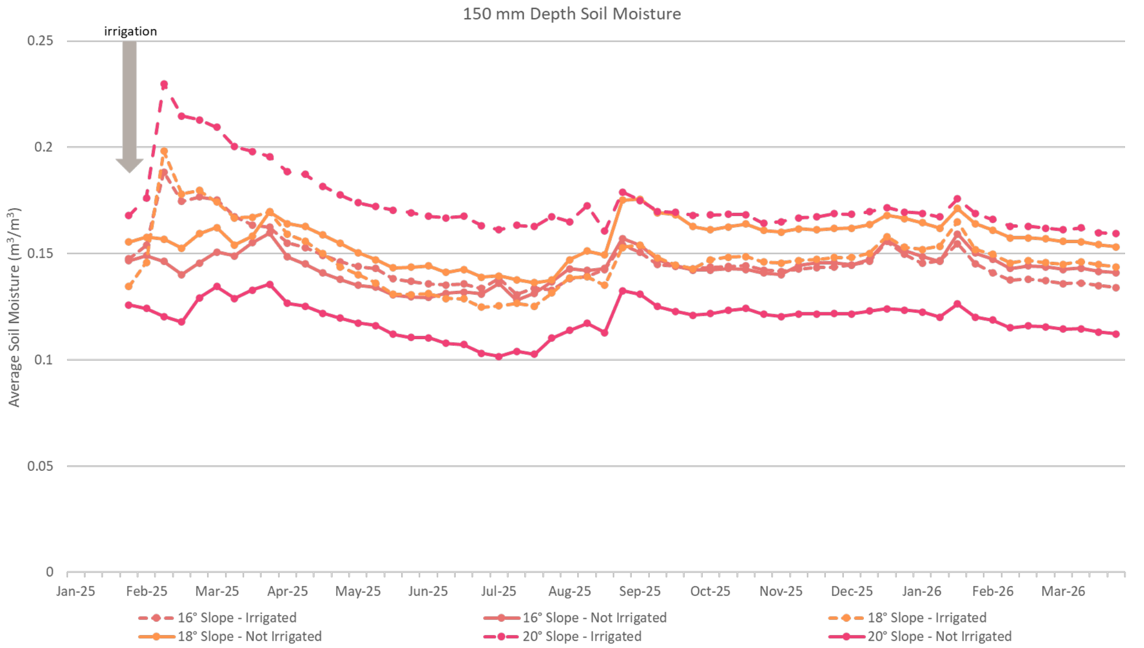


Figure 4 Mean ± 95% confidence intervals of alive *Triodia* density per 4m² across slope angles and irrigation treatments approximately one year following irrigation. The dashed line represents the early rehabilitation performance target

Soil moisture at 20 mm deep fluctuates with precipitation and irrigation more than soil moisture at 150 mm deep (Figures 5a and b). Following the irrigation event in February 2025, 20 mm-deep soil moisture in the irrigated plots is typically the same across all slope angles, suggesting similar moisture dynamics and was consistently higher than non-irrigated 18 and 20° slopes across the period surveyed (Figure 5a). This differed to soil moisture at 150 mm depth, where the irrigated 20° slopes consistently had the highest moisture (Figures 5a and b). At 150 mm deep there was less difference between the irrigated and non-irrigated plots for 16 and 18° slopes, suggesting similar moisture dynamics. It was very different for 20° slopes, suggesting higher retention of water from the irrigation. However, further monitoring of soil moisture is required across more landforms and growth media types to better understand the dynamics.



(a)



(b)

Figure 5 Soil moisture at: (a) 20 mm deep; (b) 150 mm deep for the slope angle trial

These results highlight that approximately one year following an irrigation event there appears to be little consistent effect of slope angles on the density of perennial plants. Due to over 95% of all perennial plants being *Triodia* across all monitoring events, there are stronger conclusions around the effects of slope angle on *Triodia* rather than on other perennial species seeded, including *Acacia*, *Senna* and *Maireana* species. Other parameters related to landform design that may influence vegetation outcomes could include material type, aspect, batter height and berm width. This study only provides insights into the effects of slope angles and one year following irrigation there is high variability, suggesting no strong effect of slope angle on *Triodia*. There does appear to be an effect from irrigation on vegetation outcomes, which is expected given that pulses in germination due to rainfall are known to occur throughout the Pilbara. However, the substantial rain between seeding and irrigation may have dampened the effect of the irrigated plots. Ongoing monitoring of this trial will enable stronger conclusions on the effect of slope angle on rehabilitation outcomes.

5 Discussion

These 3 trials highlight the complexity of conducting successful rehabilitation in the Pilbara and suggest that successful rehabilitation is not driven by a single variable; rather it is likely the combination of a range of practices and the field conditions experienced. Water availability appeared important for rehabilitation outcomes, particularly for the tubestock trial where dry season planting without watering in yielded very low survival, while survival in wet season planted tubestock without watering in was relatively high due to a rain event at the time of planting. Furthermore, there was a trend of higher *Triodia* densities in plots that received irrigation than plots that were not irrigated in the slope angle trial. However, the low germination rate of other species in the irrigation slope angle trial suggests that water alone was not enough to stimulate germination of these species. It is likely that complex interactions between water and seed delivery influenced the response, highlighting the need for a multifactorial approach for successful rehabilitation.

Both the seed rate and timing trial, and the slope angle trial, had treatments dominated by *Triodia* where seeding was completed using a drone. The difference in composition likely relates to seed placement and burial depth being recognised as key barriers to germination and establishment for many native species. Seeds have different burial depth requirements due to relationships with water, sunlight, nutrients and growth media (Merino-Martin et al. 2017; Dobrowlski 2019; Masarei et al. 2020). *Triodia* has been found to germinate best when placed at 5 mm deep in the soil (Masarei et al. 2019; Masarei et al. 2020), which is substantially shallower than larger seeded species in the Pilbara such as *Acacia, Senna* and *Grevillia*, which have been found to germinate from depths greater than 50 mm (Omari & Hattar 1994; Masarei et al. 2019). Achieving seed burial at the correct depth can also help manage herbivory or seeds being blown away from the soil surface (Castro et al. 2024). Further investigations into optimal seeding depth, and equipment that can reliably deliver this at large scales, is required.

The trials outlined provide early indications of some impacts on different factors relating to rehabilitation success. They also provide learnings for future trial designs, such as plot set-up for different treatments, and assist with developing future research priorities. A limitation is that results are from single-site trials; expanding replication across landforms and sites is required to strengthen the findings and broaden their applicability. Additionally, soil testing did not occur so the effect of soil characteristics on trial results cannot be determined. Future trials may yield different findings and highlight the importance of developing a strong dataset to inform rehabilitation practices.

These trials will continue to be monitored to understand longer-term outcomes; particularly through testing across multiple summers, when plant mortality can be high if there is little rain. To promote desirable rehabilitation outcomes across a range of different conditions, further work understanding plant vegetation development, seed delivery, species-specific needs and soil quality factors will occur.

6 Conclusion

Replicated, onsite field trials provide a critical evidence base for improving rehabilitation practices across mining operations. The trials presented highlight the complex range of drivers of rehabilitation success and suggest little effects due to slope angle but a likely substantial impact due to moisture availability and seeding techniques. These findings will influence operational actions, and support simplified and more defensible rehabilitation prescriptions that reduce risk and improve consistency across Pilbara environments and encourage continued improvement of rehabilitation outcomes.

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