

Direct Seeding achieves rehabilitation objectives for an operational sand mine in Southeast Queensland: A case study

Author

Johnson, CD, Thomson, M, Vermeulen, M, Waud, M, McBroom, J, Michael, RN

Published

2025

Journal Title

Ecological Engineering

Version

Version of Record (VoR)

DOI

[10.1016/j.ecoleng.2025.107724](https://doi.org/10.1016/j.ecoleng.2025.107724)

Rights statement

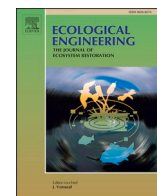
© 2025 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Downloaded from

<https://hdl.handle.net/10072/439037>

Griffith Research Online

<https://research-repository.griffith.edu.au>



Direct Seeding achieves rehabilitation objectives for an operational sand mine in Southeast Queensland: A case study

Christopher D. Johnson^{a,d,*}, Matthew Thomson^a, Michael Vermeulen^a, Mark Waud^b, James McBroom^c, Ruby N. Michael^d

^a Southern Pacific Sands, Pacific Silica Pty Ltd, Australia

^b Restoration Innovation, Healthy Land and Water, Australia

^c Statistics and Data Science, School of Environment and Science, Griffith University, Nathan, Australia

^d Green Infrastructure Research Labs (GIRLS), School of Engineering and Built Environment, Griffith University, Nathan, Australia

ARTICLE INFO

Keywords:

Direct seeding
Mine rehabilitation
Eucalyptus
Native grass
Weed management
Ecological restoration
Cost-effectiveness

ABSTRACT

Direct seeding is increasingly recognised as a practical method for ecological restoration; however, its application in post-mining rehabilitation remains limited due to concerns regarding establishment reliability, species performance, and cost-effectiveness. This study evaluates the effectiveness of direct seeding for mine rehabilitation at an operational sand mine in Southeast Queensland, with a focus on achieving compliance with Queensland's Progressive Rehabilitation and Closure Plan (PRCP) requirements.

A seed mix comprising 10 native woody species—including primary and secondary koala food trees (*Eucalyptus* and *Corymbia* spp.)—and five native grass species was applied across two sites with contrasting land-use histories. Vegetation establishment was monitored over a 36-month period, with performance assessed in terms of species richness, plant density, and the influence of non-native vegetation.

At the Native Vegetation Site, canopy tree densities substantially exceeded PRCP targets (5200 vs. 600 stems/ha), and key koala food trees also surpassed their respective benchmarks. In contrast, native grass establishment was lower than anticipated, potentially reflecting dormancy constraints, site-specific soil properties, and competition with exotic species. At the Pasture Site, the dominance of *Chloris gayana* (Rhodes grass) significantly inhibited native plant recruitment, highlighting the importance of targeted weed management.

A cost analysis indicated that direct seeding was approximately 30 % more cost-effective than tubestock planting, while supporting greater species and structural diversity. These findings demonstrate that, when implemented with appropriate site preparation and management, direct seeding represents a scalable, economically viable, and ecologically robust strategy for post-mining landscape rehabilitation.

1. Introduction

Direct seeding, while widely utilised in agricultural and mining sectors across Australia, has seen limited adoption in other contexts, particularly in Queensland. Challenges stemming from inconsistent outcomes during early trials—such as unsuitable site conditions, inadequate follow-up weed management, poor seed viability, and the absence of regionally tailored guidance—have led many land managers in the state to dismiss the method as unreliable (Zamin et al., 2018; Chenoweth EPLA and Bushland Restoration Services, 2012; Smith and Nichols, 2011). These challenges have been particularly evident in mine rehabilitation, where the primary objective is to restore native

ecosystems and ecological processes by incorporating indigenous plant species (Spain et al., 2025; Chenoweth EPLA and Bushland Restoration Services, 2012; Pinkard, 1992). In this context, traditional methods involving the manual planting of container-grown stock have dominated. However, while effective in some instances, these methods are labour-intensive, costly, and impractical for large-scale rehabilitation efforts (Department of Industry, Sciences, and Resources DISR, 2016; Palmerlee and Young, 2010; Corbett, 1999).

Direct seeding has emerged as a promising, cost-effective alternative for rehabilitating extensive disturbed areas, such as those left by mining and quarrying activities (Turner et al., 2022; Mattiske, 2016; Pryde and Duncan, 2015; Woodall, 2014). Its advantages include faster

* Corresponding author at: Southern Pacific Sands, Pacific Silica Pty Ltd, Australia.

E-mail address: christopher.johnson5@griffithuni.edu.au (C.D. Johnson).

<https://doi.org/10.1016/j.ecoleng.2025.107724>

Received 9 February 2025; Received in revised form 13 May 2025; Accepted 2 July 2025

Available online 29 July 2025

0925-8574/© 2025 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

revegetation rates, lower mortality, and the creation of restoration sites that mimic natural ecosystems (Palmerlee and Young, 2010; Northern Yorke Natural Resources Management (NYNRM), 2011). Despite these benefits, the method has seen uneven adoption across Australia, with Queensland lagging significantly compared to regions like Western Australia, South Australia, and New South Wales, where successful outcomes have been achieved through better environmental alignment and comprehensive guidance (Carr et al., 2009; NSW Mining, 2014; Stokes, 2010). While grey literature extensively documents direct seeding in mining (Turner et al., 2022; NSW Mining, 2014; Chandrasekaran et al., 2000) and agriculture (Pryde and Duncan, 2015; Scheltema, 1993; Piggott et al., 1987), peer-reviewed studies remain scarce, with only a handful addressing its practical applications in mine rehabilitation (Gravina et al., 2011; Huxtable et al., 2005; Semple et al., 1999; Knight et al., 1997; Barron and Dalton, 1996). The lack of rigorous academic attention has limited the development of universally applicable practices and region-specific techniques.

One of the key considerations in ecological restoration is the selection of appropriate plant species. The relative merits of native and exotic species have been the subject of ongoing debate within restoration ecology. Native species are generally favoured for their ecological suitability, capacity to support local biodiversity, and potential to contribute to long-term ecosystem resilience (Spain et al., 2025; Chenoweth EPLA and Bushland Restoration Services, 2012). Conversely, exotic pasture species might instead be employed to achieve rapid ground cover and mitigate erosion, particularly in highly disturbed environments (Gravina et al., 2011; Smith and Nichols, 2011). Although such species may offer short-term stabilisation benefits, they can also inhibit the recruitment of native flora and disrupt natural successional processes (Cole and Lunt, 2005; Chandrasekaran et al., 2000). As such, understanding how different species compositions influence vegetation establishment and ecosystem recovery is critical to ensuring that restoration outcomes meet both regulatory compliance requirements and broader ecological objectives.

Critical barriers to successful direct seeding include ensuring species provenance, refining seed collection and dispersal methods, and accounting for environmental factors such as temperature, rainfall, erosion, and invasive species competition (Spain et al., 2025; Grossnickle and Ivetić, 2017; Ralph, 2009; Pinkard, 1992). Addressing these challenges is essential to improving the method's reliability and broader adoption across Queensland and other regions. To this end, Southern Pacific Sands, a sand mine near Bribie Island in Southeast Queensland, has undertaken small-scale direct seeding trials since 2018. These trials have sought to overcome common obstacles while meeting government-mandated rehabilitation criteria under the mine's Progressive Rehabilitation and Closure Plan (PRCP). The PRCP, now required for all mines with site-specific environmental authorities (EA) in Queensland, mandates the establishment of a self-sustaining vegetation community. Specifically, Southern Pacific Sand's rehabilitated landform must support 600 stems per hectare of canopy species, including quotas for Primary Koala Food Trees (PKFT), Secondary Koala Food Trees (SKFT), and Glossy Black Cockatoo Feed Trees (GBCFT) (Southern Pacific Sands, 2023).

This study evaluates the impact of direct seeding a mix of 10 native woody plant species, five native grass species, and an exotic pasture mix at one trial site. The goal was to inform the mine's rehabilitation strategy by refining direct seeding techniques and balancing ecological restoration with economic and operational considerations. The findings aim to create post-mining landscapes that meet PRCP requirements, while demonstrating the potential of direct seeding as a scalable, cost-effective alternative to traditional tubestock planting in Southeast Queensland.

2. Methods

2.1. Study site

This study was conducted at an active sand mine in Southeast Queensland, approximately 60 km north of Brisbane and 1.5 km west of Moreton Bay (−27.08971, 153.07373). The site is situated at a low elevation (<3.0 m AHD) and is heavily influenced by its proximity to the coast. The landscape includes several water-filled pits, remnants of prior mining activities (Mary Maher and Associates, 1994). Soils in the vicinity are predominantly siliceous or calcareous sands (rudosols and tenosols), podosols, and organosols, as characterised by Wilson and Taylor (2012).

Historically, the area was used for grazing and forestry before the commencement of sand mining operations (Mary Maher and Associates, 1994). Over half of the area comprises highly disturbed vegetation that is less than 30 years old. The remaining vegetation corresponds to four distinct regional ecosystems (Table 1), with variation due to local topography (Queensland Herbarium, 2023).

2.2. Site preparation

The study sites were located on the western bank of a water-filled void at the sand mine. Both sites were initially dominated by a grassy ecosystem with significant weed biomass. Site preparation began in April 2021, involving slope reconstruction targeting a "gentle" to "moderate" slope (Machar et al., 2015; Witheridge, 2012) using a high-clay-content coarse reject material (50 % <6 µm and 95 % <64 µm) shaped with a bulldozer. Following slope reconstruction, a 100-mm layer of stockpiled topsoil, stripped from the mine pathway and stored

Table 1

List of Regional Ecosystems adjacent to the study sites.

Regional Ecosystem	Short description
12.2.5	Open forest to low closed forest. Species can include <i>Corymbia intermedia</i> , <i>Lophostemon confertus</i> , <i>Banksia integrifolia</i> subsp. <i>integrifolia</i> , <i>B. aemula</i> , <i>Callitris columellaris</i> , <i>Acacia</i> spp., <i>Livistona</i> spp. and <i>Endiandra sieberi</i> . <i>Melaleuca quinquenervia</i> in swales. Understorey generally shrubby and can include vine forest species. Occurs on Quaternary coastal dunes, beach ridges and sandy banks of coastal streams. Contains Palustrine.
12.2.6	<i>Eucalyptus racemosa</i> subsp. <i>racemosa</i> , <i>Corymbia intermedia</i> , <i>C. gummifera</i> , <i>Angophora leiocarpa</i> and <i>E. pilularis</i> shrubby or grassy woodland to open forest. Occurs on Quaternary coastal dunes and beaches. Dunes with deeply leached soils. Not a Wetland.
12.3.5	<i>Melaleuca quinquenervia</i> open forest to woodland. Understorey depends upon duration of water logging; sedges and ferns, especially <i>Blechnum indicum</i> , in wetter microhabitats and grasses and shrubs in drier microhabitats. Ground layer species include the grasses <i>Leersia hexandra</i> and <i>Imperata cylindrica</i> , the sedges/rushes, <i>Machaerina rubiginosa</i> , <i>Gahnia sieberiana</i> , <i>Lepironia articulata</i> , <i>Schoenus brevifolius</i> and <i>Schoenus scabripes</i> and the fern <i>Lygodium microphyllum</i> . Other tree species that may be present as scattered individuals or clumps include <i>Lophostemon suaveolens</i> , <i>Eucalyptus robusta</i> , <i>E. tereticornis</i> , <i>E. bancroftii</i> , <i>E. latisinensis</i> , <i>Corymbia intermedia</i> , <i>Melaleuca salicina</i> , <i>Livistona australis</i> , <i>Casuarina glauca</i> , <i>Endiandra sieberi</i> . <i>Melastoma malabathricum</i> subsp. <i>malabathricum</i> , <i>Glochidion sumatranum</i> and <i>Melicope elleryana</i> are often in the understorey. Occurs on Quaternary alluvium in coastal areas. Palustrine.
12.3.6	<i>Melaleuca quinquenervia</i> +/- <i>Eucalyptus tereticornis</i> , <i>Lophostemon suaveolens</i> , <i>Corymbia intermedia</i> open forest to woodland with a grassy ground layer dominated by species such as <i>Imperata cylindrica</i> . <i>Eucalyptus tereticornis</i> may be present as an emergent layer. <i>Eucalyptus seeana</i> may also occur in this ecosystem to the south and east of Brisbane. Occurs on Quaternary floodplains and fringing drainage lines in coastal areas. Palustrine.

Queensland Herbarium. (2023). Regional Ecosystem Description Database. Version 13. Department of Environment & Science. Brisbane.

for less than six months, was applied to the reconstructed surface. To alleviate compaction from heavy machinery, the landform was cross-rippled using a bulldozer, creating a conducive environment for root penetration and water infiltration (Table 2).

Site boundaries were established using a Garmin GPS device and imported into QGIS Desktop 3.2 Odense for spatial mapping. Metal stakes, capped with yellow safety markers, demarcated the boundary. Native Vegetation Site was allocated for native vegetation restoration, while Pasture Site was designated for pasture establishment (Fig. 1). Within each site, three 50 × 2 m seed rows were created and marked with white surveyor pegs at opposite corners.

2.3. Seed mix & application

Manual hand-broadcasting of seed mixes was conducted in March 2021. The native seed mix, consisting of 15 native woody and grass species (listed in Table 2), was applied to both sites. For *Acacia fimbriata* and *A. concurrens*, seed pre-treatment using the “hot water method” was conducted in accordance with Dalton (1993) and Ralph (2009). All other species in the mix were applied without pre-treatment.

A second seed mix, the Norco Gympie Coastal Cattle Mix (referred to as the pasture seed mix), was applied exclusively to the Pasture Site. This mix comprised eight exotic species: *Chloris gayana* cv. ‘Epica’, *Chloris gayana* cv. ‘Reclaimer’, *Megathyrsis maximus* cv. ‘Gatton’, *Macroptilium atropurpureum* cv. ‘Aztec’, *Stylosanthes* spp. cv. ‘Stylo’, *Chamecrista rotundifolia* cv. ‘Wynn’, *Trifolium repens* cv. ‘Haifa’, and *Echinochloa esculenta* cv. ‘Jap’ (Table 2). No pre-treatment was applied to the seeds in this mix.

Table 2

Breakdown of Native Vegetation Site and Pasture Site characteristics for the direct seed trials.

	Native Vegetation Site	Pasture Site
Topsoil	100mm	100mm
Slope gradient	12.3%	12.3%
Restoration goal	Native ecosystems	Grazing
	<u>Grass (0.7kg)</u>	<u>Grass (0.7kg)</u>
	<i>Bothriochloa bladhii</i>	<i>Bothriochloa bladhii</i>
	<i>Capillipedium spicigerum</i>	<i>Capillipedium spicigerum</i>
	<i>Dichanthium sericeum</i>	<i>Dichanthium sericeum</i>
	<i>Heteropogon contortus</i>	<i>Heteropogon contortus</i>
	<i>Themeda triandra</i>	<i>Themeda triandra</i>
	<u>Woody plant (0.2kg)</u>	<u>Woody plant (0.2kg)</u>
	<i>Acacia concurrens</i>	
	<i>Acacia falcata</i>	<i>Acacia concurrens</i>
	<i>Acacia fimbriata</i>	<i>Acacia falcata</i>
	<i>Allocasuarina littoralis</i> (GBCFT)	<i>Acacia fimbriata</i>
	<i>Alphitonia excelsa</i>	<i>Allocasuarina littoralis</i> (GBCFT)
	<i>Corymbia intermedia</i> (SKFT)	<i>Alphitonia excelsa</i>
	<i>Eucalyptus bancroftii</i> (PKFT)	<i>Corymbia intermedia</i> (SKFT)
	<i>Eucalyptus seeana</i> (SKFT)	<i>Eucalyptus bancroftii</i> (PKFT)
	<i>Eucalyptus tereticornis</i> (PKFT)	<i>Eucalyptus seeana</i> (SKFT)
	<i>Melaleuca linarrifolia</i>	<i>Eucalyptus tereticornis</i> (PKFT)
	<i>Melaleuca quinquenervia</i> (SKFT)	<i>Melaleuca linarrifolia</i>
		<i>Melaleuca quinquenervia</i> (SKFT)
Seed mix		<u>Pasture (4.0kg)</u>
		<i>Chloris gayana</i> cv ‘Epica’
		<i>Chloris gayana</i> cv ‘Reclaimer’
		<i>Megathyrsis maximus</i> cv ‘Gatton’
		<i>Macroptilium atropurpureum</i> cv ‘Aztec’
		<i>Stylosanthes</i> spp. cv ‘Stylo’
		<i>Chamecrista rotundifolia</i> cv ‘Wynn’
		<i>Trifolium repens</i> cv ‘Haifa’
		<i>Echinochloa esculenta</i> cv ‘Jap’

2.4. Post-seed management and monitoring

At Native Vegetation Site, weed management was conducted throughout the monitoring period, with treatments applied every three months during the first year and quarterly thereafter. Weed control methods included a combination of strip control, following Dalton (1993), and spot-spraying based on methods from Chenoweth EPLA and Bushland Restoration Services (2012). Weedmaster Duo (containing 360 g/L glyphosate) was applied using a knapsack sprayer, supplemented by a non-ionic penetrant/surfactant (Pulse, 1020 g/L Polyether modified polysiloxane) and a dye marker (Tru-Blue spray indicator; 105 g/L Acid Blue Dye 9 Sodium Salt) at rates of approximately 2.0 L/ha, 0.4 L/ha, and 0.5 L/ha, respectively, across 10 site visits. Weed management was not implemented at Pasture Site, where the objective was to allow non-native pasture species to establish.

To evaluate the success of the direct seeding and management strategies, vegetation monitoring was undertaken at 12- and 36-months post-sow. These surveys documented species richness and density of native woody plants and grasses, and the height and cover of non-native species within the seeded rows, using monitoring techniques adapted from the Queensland Herbarium *BioCondition Assessment Manual* v2.2 (Eyre et al., 2015). Expected densities for native woody plants and grasses were derived from seed viability and establishment data provided by Australian Seed Labs Pty Ltd., as well as data from Dalton (1993), to support comparative analysis. Pre-emergent losses were not quantified in this study.

2.5. Project cost-effectiveness

Operational feasibility and minimal input requirements (e.g., labour and materials) were assessed to compare the cost-effectiveness of direct seeding with tubestock planting. Cost estimates were based on the costs associated with seed sourcing and procurement, manual labour hours (e.g., seeding and follow-up maintenance), and equipment and operational expenses (e.g., site preparation). Cost estimations for both methods were derived from a combination of direct sources (e.g., invoices and field records) and indirect costs related to the study, supplemented by the collective field experience of the author’s (cumulatively 60 years). This approach highlights the practical and economic considerations involved in mine rehabilitation efforts.

2.6. Statistical analysis

Statistical analyses were conducted to evaluate differences in seedling establishment and vegetation structure between the two trial sites—one sown with a native species mix and the other with an exotic pasture mix. The primary performance indicators assessed were species richness, plant density, and average height, which were selected for their relevance to early-stage establishment, competition, and compliance with regulatory rehabilitation criteria.

Native grass seedling richness, being count-based data, was analysed using a Poisson generalised linear model (GLM). This approach was chosen due to the discrete nature of the data and its suitability for modelling count outcomes.

The density of native grasses, along with the richness and density of native woody plants, were evaluated using analysis of covariance (ANCOVA), with non-native plant height included as a covariate to account for its potential influence on understory performance. Non-native plant height was analysed separately using Welch’s *t*-test to account for unequal variances between sites.

All statistical analyses were performed using IBM SPSS Statistics (Version 28.0.1.1, Armonk, NY: IBM Corporation), with significance assessed at $\alpha = 0.05$. Where applicable, model residuals were visually inspected to confirm assumptions of normality and homoscedasticity.

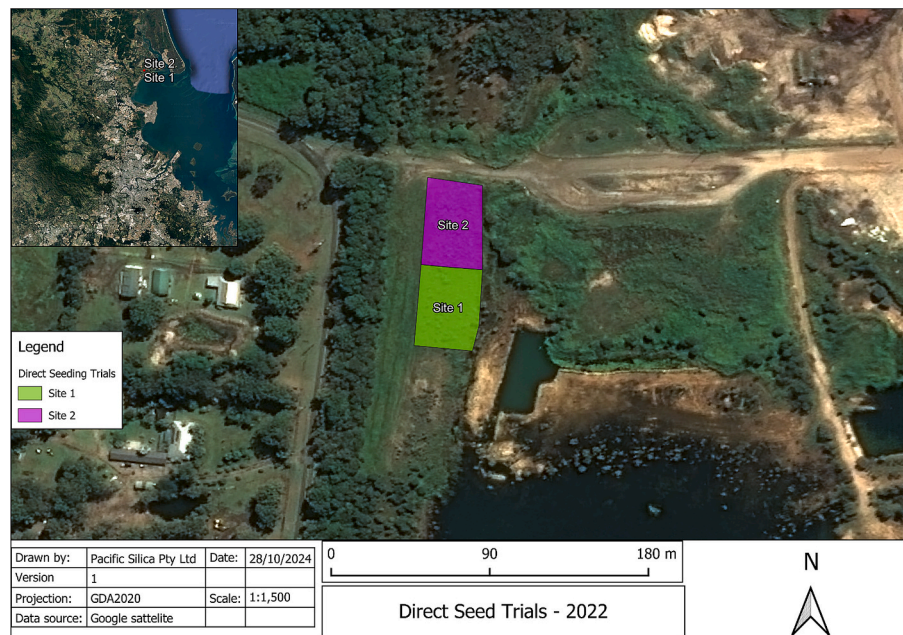


Fig. 1. Aerial image of rehabilitation sites 1 (Native Vegetation Site) & 2 (Pasture Site) at the sand min.

3. Results

Weather conditions varied significantly over the study period, with above-average temperatures and rainfall from April 2021 to May 2022, accumulating to 2378 mm in the 12 months following direct seeding. Despite these conditions, all 15 direct-seeded species (10 woody plants and 5 grasses) successfully established across both sites, although species densities were generally lower than anticipated.

3.1. Native grass establishment

At the Native Vegetation Site, four of the five seeded native grass species established within the first 12 months, though only two species persisted at 36 months (Table 3). At the Pasture Site, three grass species were recorded at both time points. Both sites experienced minor, non-significant reductions in mean native grass species richness between 12 and 36 months (Fig. 2A).

At 12 months, native grass density reached approximately 5800 individuals per hectare at the Native Vegetation Site and 1900 individuals per hectare at the Pasture Site (Fig. 2B). These values corresponded to observed establishment rates of 0 %–5.9 % and 0 %–1.8 % of expected densities, respectively. By 36 months, densities had slightly declined to around 5500 and 1800 individuals per hectare, with observed densities of 0 %–8.0 % and 0 %–1.8 %, respectively. Among species, *Chrysopogon spicigerum* and *Bothriochloa bladhii* exhibited the highest mean densities at 36 months (2650 and 817 stems/ha), while *Themeda triandra* and *Dichanthium sericeum* had lower densities (800 and 272 stems/ha) (Table 3).

Native grass density at 12 months and 36 months was higher at the Native Vegetation Site than at the Pasture Site, although the differences approached but did not reach statistical significance ($t = 2.79$, $df = 5$, $p = 0.086$ and $t = 2.81$, $df = 5$, $p = 0.080$ respectively). Within-site comparisons revealed no significant differences in native grass densities between 12 months and 36 months.

3.2. Woody plant establishment

At the Native Vegetation Site, nine of the ten woody species established at both 12 and 36 months. At the Pasture Site, four species established at 12 months, declining to three species by 36 months

(Table 3).

At 12 months, mean woody plant density was approximately 8800 stems/ha at the Native Vegetation Site and 2700 stems/ha at the Pasture Site, representing 0 %–5.3 % and 0 %–5.1 % of expected values, respectively. By 36 months, densities declined to 5200 and 3200 stems/ha, respectively (0 %–4.2 % and 0 %–6.1 % of expected). Key rehabilitation targets—Koala Primary Food Trees (*Eucalyptus tereticornis*), Secondary Food Trees (*Corymbia intermedia*, *Eucalyptus seeana*, *Melaleuca quinquenervia*), and Glossy Black Cockatoo Feed Trees (*Allocasuarina littoralis*)—established at average densities of 767, 1433, and 100 stems/ha by 36 months (Table 3).

Woody plant species richness was significantly higher at the Native Vegetation Site compared to the Pasture Site at 12 months ($R^2 = 0.951$, $df = 5$, $p = 0.011$), and marginally at 36 months ($R^2 = 0.854$, $df = 5$, $p = 0.056$).

Using ANCOVA to control for non-native plant height, eucalypt species richness and density remained significantly higher at the Native Vegetation Site than at the Pasture Site at 12 months ($R^2 = 0.951$, $df = 5$, $p = 0.011$ and $R^2 = 0.914$, $df = 5$, $p = 0.025$, respectively) and 36 months ($R^2 = 1.000$, $df = 5$, $p < 0.001$ and $R^2 = 0.833$, $df = 5$, $p < 0.001$). Eucalypt richness increased from three species at 12 months to four at 36 months ($R^2 = 1.00$, $df = 5$, $p < 0.001$), while richness at the Pasture Site declined from 0.7 species to zero ($R^2 = 0.899$, $df = 5$, $p = 0.032$). Eucalypt density remained relatively stable at both sites over time.

No significant differences were found between sites or time points for non-eucalypt woody species richness or density (Fig. 2C and D). At 36 months, *Acacia concurrens* and *Acacia falcata* were the most successful non-eucalypt species (1033 and 1017 stems/ha), while *Petalostigma pubescens* failed to establish.

3.3. Non-native plant height

Non-native plant height was significantly greater at the Pasture Site than at the Native Vegetation Site at both 12 months ($t = -9.45$, $df = 5$, $p = 0.001$) and 36 months ($t = -22.21$, $p < 0.001$) (Fig. 2G). Between the 12- and 36-month assessments, both the Native Vegetation Site and Pasture Site exhibited significant increases in non-native plant height ($t = -3.91$, $df = 5$, $p = 0.04$ and $t = -4.83$, $df = 5$, $p = 0.018$ respectively).

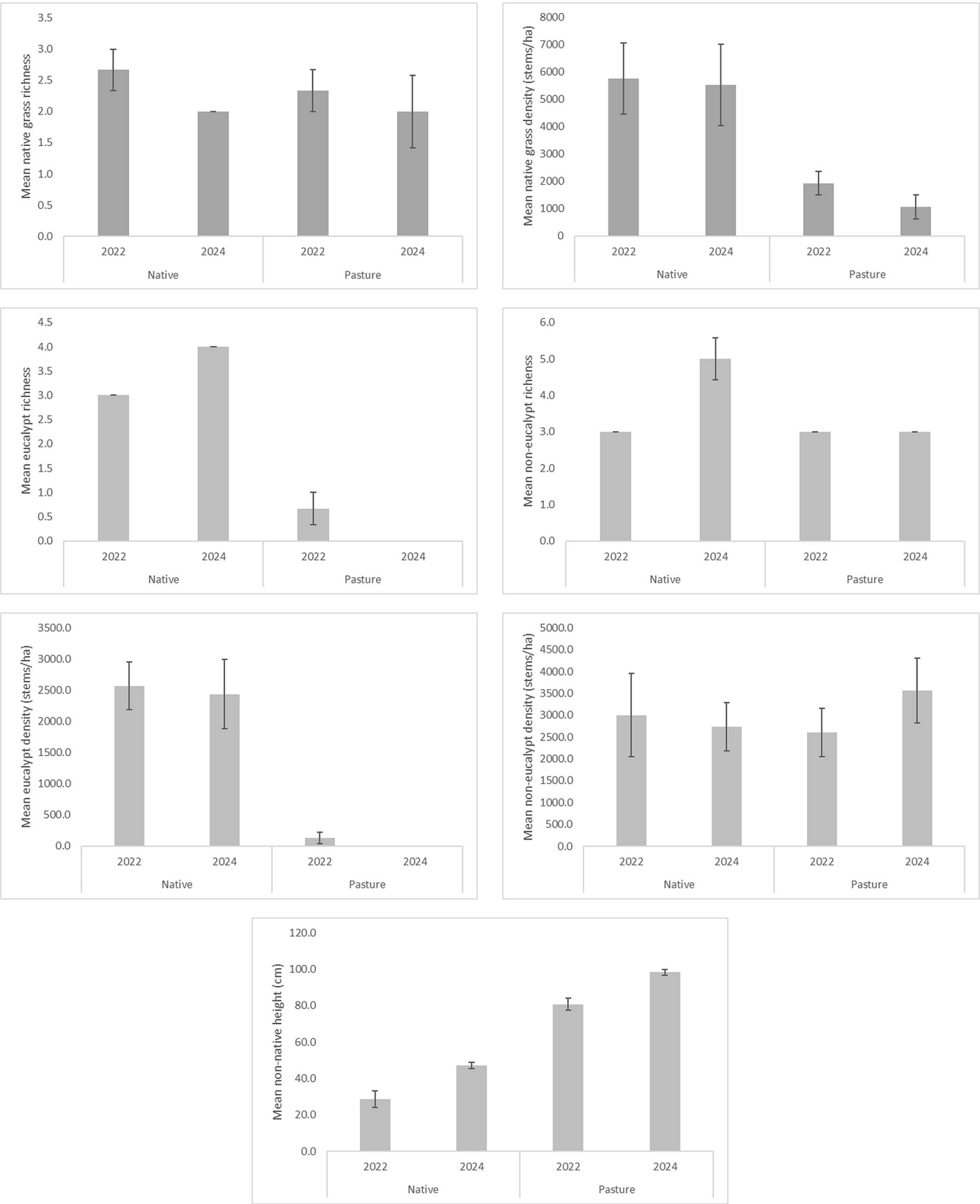


Fig. 2. Mean native grass richness (A), native grass density (B), eucalypt richness (C), non-eucalypt richness (D), eucalypt density (E), non-eucalypt density (F), and non-native height (G) observed across the study sites at 12-months and 36-months post-sow. Error bars display the standard error about the mean.

Table 3

Characteristics and occurrence of directed seeded native grasses, shrubs, and trees at two rehabilitation sites. Observed plant densities (individuals/ha, $\pm$ standard error) and establishment rates (...%) for each species averaged across direct seeded rows within each site ($n = 3$). Establishment rates represent the percent difference between expected and observed plant densities based on seed viability data supplied by (*) Australian Seed Labs Pty Ltd. or extracted from (†) Dalton (1993). Observed means were derived from monitoring data at 12- and 36-months post-sow.

Seed mix	Species	Seed volume/ row (g/100m ²)	Seeds/ g	Viability (%)	Expected density / seeded row (no./ha)	Observed mean density / seeded row (no./ha)			
						Native Vegetation Site 2022	Native Vegetation Site 2024	Pasture Site 2022	Pasture Site 2024
Native Grass	<i>Bothriochloa bladhii</i>	33.3	125	37*	154,000	2100.0 $\pm$ 360.6 (1.4 %)	1233.3 $\pm$ 375.6 (0.8 %)	533.3 $\pm$ 145.3 (0.4 %)	400.0 $\pm$ 305.5 (0.2 %)
	<i>Capillipedium spicigerum</i>	33.3	125	13*	54,000	3200.0 $\pm$ 1179.0 (5.9 %)	4300.0 $\pm$ 1115.0 (8.0 %)	1000.0 $\pm$ 251.7 (1.8 %)	1000.0 $\pm$ 66.7 (1.8 %)
	<i>Dichanthium sericeum</i>	33.3	500	89*	1,481,000	200.0 $\pm$ 200.0 (<0.1 %)	0	Did not emerge	Did not emerge
	<i>Heteropogon contortus</i>	8.3	140	78*	91,000	266.7 $\pm$ 266.7 (0.2 %)	0	400.0 $\pm$ 115.5 (0.4 %)	400.0 $\pm$ 100.0 (0.4 %)
	<i>Themeda triandra</i>	8.3	120	42*	42,000	Did not emerge	Did not emerge	Did not emerge	Did not emerge
	<i>Acacia concurrens</i>	4.1	65	90 [†]	24,000	1266.7 $\pm$ 328.3 (5.3 %)	800.0 $\pm$ 57.7 (3.3 %)	933.3 $\pm$ 366.7 (3.9 %)	1133.3 $\pm$ 120.2 (4.7 %)
	<i>Acacia falcata</i>	3.1	82	90 [†]	23,000	800.0 $\pm$ 351.2 (3.5 %)	966.7 $\pm$ 366.7 (4.2 %)	800.0 $\pm$ 173.2 (3.5 %)	1066.7 $\pm$ 405.5 (4.6 %)
Woody Plant	<i>Acacia fimbriata</i>	2.3	80	90 [†]	17,000	600.0 $\pm$ 230.9 (3.5 %)	433.3 $\pm$ 88.2 (2.5 %)	866.7 $\pm$ 66.7 (5.1 %)	1033.3 $\pm$ 409.5 (6.1 %)
	<i>Allocasuarina littoralis</i> (GBCFT)	0.6	500	90 [†]	27,000	33.3 $\pm$ 33.3 (0.1 %)	100.0 $\pm$ 100.0 (0.3 %)	Did not establish	Did not establish
	<i>Alphitonia excelsa</i>	5.4	20	50 [†]	1000	Did not establish	Did not establish	Did not establish	Did not establish
	<i>Corymbia intermedia</i> (SKFT)	6.2	410	80 [†]	20,000	600.0 $\pm$ 100.0 (3.0 %)	600.0 $\pm$ 100.0 (3.0 %)	Did not establish	Did not establish
	<i>Eucalyptus bancroftii</i> (PKFT)	3.1	300	90 [†]	84,000	866.7 $\pm$ 290.6 (1.0 %)	666.7 $\pm$ 233.3 (0.8 %)	Did not establish	Did not establish
	<i>Eucalyptus seeana</i> (SKFT)	2.7	340	90 [†]	83,000	600.0 $\pm$ 433.3 (0.7 %)	400.0 $\pm$ 152.8 (0.5 %)	133.3 $\pm$ 88.2 (0.2 %)	0
	<i>Eucalyptus tereticornis</i> (PKFT)	6.1	320	90 [†]	176,000	433.3 $\pm$ 218.6 (0.2 %)	766.7 $\pm$ 218.6 (0.4 %)	Did not establish	Did not establish
	<i>Melaleuca linarrifolia</i> / <i>quinquenervia</i> (SKFT)	0.1	1700	90 [†]	15,300	300.0 $\pm$ 152.8 (2.0 %)	433.3 $\pm$ 166.7 (2.8 %)	Did not establish	Did not establish

* Supplied by Australian Seed Labs Pty Ltd.

[†] extracted from Dalton (1993).

3.4. Project costings – canopy trees

direct seeding as the primary method for establishing only canopy trees.

The total cost of direct seeding was \$17,720.14, compared to a projected cost of \$25,569.05 for tubestock planting (Tables 4 and 5), indicating a potential cost saving of approximately 30 % when using

Table 4

Costs of direct seeding at Native Vegetation Site and Pasture Site over 36 months.

Item	Unit cost (\$)	Unit	Quantity	Total cost (\$)	Comments
Earthworks	\$150.00	hour	8	1200.00	Slope profiling, battering, and topsoil spreading using a bulldozer
Native grass seed blend	\$110.00	kilogram	0.7	77.00	Includes seed and bulking agent (vermiculite), applied to both sites
Woody plant seed blend	\$0.78	gram	144.8	112.90	Seed only, applied to Native Vegetation Site & 2
Pasture seed blend	\$16.80	kilogram	1.8	30.24	Seed only, applied to Pasture Site only
Labour – seeding	\$70.00	hour	2	140.00	Hand-broadcasting of seed blends
Labour – maintenance	\$80.00	hour	202	16,160.00	Weed management by a 2-person team over the 36-month monitoring period.
Plant loss & replacement				0.00	Estimated at 0 % in the present study, as the trial significantly exceeded all PRCP criteria, eliminating the need for replacement of lost individuals.
			Total	\$17,720.14	Cost of rehabilitation 2 $\times$ 0.18 ha rehabilitation sites

This table outlines the recorded costs associated with the direct seeding project conducted at Native Vegetation Site (~0.18 ha) and Pasture Site (~0.18 ha). Costs include seed procurement, site preparation, and post-seeding maintenance.

Table 5

Projected costs of tubestock planting at Native Vegetation Site and Pasture Site over 36 months.

Item	Unit cost (\$)	Unit	Quantity	Total cost (\$)	Comments
Earthworks	\$150.00	hours	8	1200.00	Slope profiling, battering, and topsoil spreading using a bulldozer
Nursery-grown tubestock	\$2.80	tubestock	221	618.80	Canopy trees only; excludes native grasses and pasture species
Labour – site preparation	\$80.00	hours	5.5	440.80	Planting hole preparation (digging and pre-watering) by a 2-person team
Labour – planting additives	\$1.44	tubestock	221	318.24	Includes planting gel, fertiliser, plant guards, and bamboo stakes
Labour – planting	\$70.00	hours	36.7	2569.70	Planting by a 2-person team
Labour – maintenance + consumables	\$80.00	hours	202	16,160.00	Watering and weed management by a 2-person team over 36-months.
			Subtotal	21,307.54	
Plant loss & replacement				4261.51	Estimated at 20 % of the subtotal, this figure accounts for procurement, labour, and maintenance costs. It represents a conservative estimate informed by industry experience and is deemed necessary due to the narrow margin for achieving the PRCP minimum criteria for canopy tree density.
			Total	\$25,569.05	Cost of rehabilitation 2 × 0.18 ha rehabilitation sites

This table presents estimated costs for a hypothetical tubestock planting project to achieve the PRCP canopy tree target (600 trees/ha) at the same sites (~0.36 ha). Estimates assume the engagement of an in-house nursery and exclude native grasses and pasture species for direct comparison with the direct seeding approach.

4. Discussion

4.1. Performance of direct seeding for native trees

This case study demonstrates the effectiveness of direct seeding as a method for re-establishing native woody vegetation, particularly koala food trees (*Eucalyptus* and *Corymbia* spp.), on a rehabilitated sand mine in Southeast Queensland. Germination and establishment rates observed in this study are broadly consistent with findings from grey literature (Pryde and Duncan, 2015; Dalton, 1993) and peer-reviewed research on direct seeding in mined landscapes (Huxtable et al., 2005; Semple et al., 1999; Knight et al., 1997; Barron and Dalton, 1996).

Importantly, canopy tree densities achieved through direct seeding substantially exceeded the targets specified under the site's Progressive Rehabilitation and Closure Plan (PRCP). At 36 months post-seeding, the Native Vegetation Site supported an average of 5200 stems/ha—nearly nine times the required density of 600 stems/ha. Similarly, species-specific targets were also surpassed, with Primary Koala Food Trees (PKFTs) and Secondary Koala Food Trees (SKFTs) reaching densities of ~683 and ~489 stems/ha, respectively, compared to targets of 150 and 100 stems/ha (Southern Pacific Sands, 2023). These outcomes highlight the potential of direct seeding to meet regulatory requirements while offering a more cost-effective alternative to tubestock planting, achieving high native plant densities with lower labour and input costs.

4.2. Native grass establishment and associated challenges

The results also demonstrate the potential of direct seeding to reintroduce native grasses to post-mining landscapes, though with variable success. Native grasses established at both the Native Vegetation and Pasture Sites, but species densities were generally lower than expected based on supplier viability estimates. This shortfall reflects known challenges in native grass recruitment, including site-specific environmental constraints, species-specific germination requirements, and seed dormancy mechanisms (Chivers and Raulings, 2015; Huxtable et al., 2005; Cole and Lunt, 2005; Semple et al., 1999).

Species such as *Themeda triandra* and *Dichanthium sericeum* exhibited limited persistence, whereas *Capillipedium spicigerum* and *Bothriochloa bladhii* showed stronger performance, indicating differential responses to the site's physical and biological conditions. These outcomes highlight the importance of tailoring seed mixes and management strategies to species-specific traits (Cole and Waters, 1997a,b). The findings further emphasise the need for adaptive management and site preparation approaches—particularly where soil conditions, competition, or climatic variability may inhibit germination and early growth.

While the observed densities were below the estimated maximum

potential for several species, the successful recruitment of native grasses—especially under challenging competitive conditions—underscores the promise of direct seeding as a restoration tool. To optimise outcomes, further refinement of seed pre-treatment protocols and post-sowing management strategies (e.g., moisture retention, targeted weed suppression) may be warranted.

4.3. The influence of non-native plant height on direct seeding outcomes

The results of this study underscore the critical influence of non-native vegetation on the outcomes of direct seeding, particularly in competitive rehabilitation environments. Non-native plant height was significantly greater at the Pasture Site, where exotic pasture grasses—most notably *Chloris gayana* (Rhodes grass)—formed a dominant monoculture by 36 months post-seeding. This aggressive growth likely suppressed native species recruitment and reduced overall diversity, with only a limited number of woody species, primarily *Acacia* spp., persisting under these conditions.

Although *C. gayana* is commonly used for fodder and ground stabilisation, its high growth rate, adaptability, and capacity to outcompete native flora have led to its classification as an environmental weed in Southeast Queensland (Brisbane City Council (BCC), 2015). These findings align with previous studies (e.g., Huxtable et al., 2005; Semple et al., 1999) that document the negative impacts of exotic grasses on native vegetation, particularly where soil conditions have been modified for pasture use.

Encroachment of *C. gayana* from the Pasture Site into the adjacent Native Vegetation Site—observed as early as 12 months post-seeding—highlights the risk of weed spread into areas undergoing ecological restoration. While weed control efforts at the Native Vegetation Site were likely effective in limiting this impact, unchecked growth at the Pasture Site exacerbated competitive pressures on establishing natives. This supports recommendations in the grey literature (Pryde and Duncan, 2015; Dalton, 1993) for stringent weed management, particularly during early plant establishment phases.

Differences in non-native plant height and associated vegetation dynamics between the two sites illustrate the benefits of proactive weed control in enhancing native species recruitment. These results are consistent with previous findings (e.g., Gibson-Roy and Delpratt, 2015; Chenoweth EPLA and Bushland Restoration Services, 2012), which identify weed suppression and ongoing site management as critical to successful direct seeding implementation. In the present study, such management likely contributed to the Native Vegetation Site's superior performance in establishing target species, including PKFTs, SKFTs, and Glossy Black Cockatoo Feed Trees.

4.4. The influence of other factors on the direct seeding of native grasses

The variable performance of native grasses in this study, particularly *Themeda triandra* and *Dichanthium sericeum*, highlights the ecological complexity associated with their recruitment via direct seeding. Observed low densities and limited persistence in some species may reflect dormancy mechanisms that require specific environmental triggers—such as fire, temperature fluctuations, or seasonal rainfall—to break dormancy and initiate germination (Farley et al., 2013; Wagner et al., 2011; Gibson-Roy et al., 2007). As such, dormancy-breaking treatments, including mechanical scarification or chemical stimulants, may be warranted to improve establishment rates for species exhibiting delayed or erratic germination responses (Clarke and French, 2005; Lodge and Whalley, 1981; Mott, 1978).

Additionally, temporal variability in environmental conditions during the monitoring period may have limited the germination window for some species (Chivers and Raulings, 2015; Cole and Waters, 1997a). As ecological conditions continue to evolve post-rehabilitation, there remains potential for future recruitment of species that have not yet germinated, particularly those with longer dormancy cycles. Continued monitoring will therefore be essential to evaluate the full trajectory of native grass establishment and persistence.

The application of topsoil at both trial sites may also have influenced germination outcomes. While topsoil can enhance early establishment by improving soil structure and moisture retention, it may inadvertently disadvantage native grasses that are adapted to low-nutrient, disturbance-prone substrates (Gibson-Roy, 2023). Previous research has shown that certain species—*T. triandra* in particular—respond more favourably to raw or oxidised mine spoil than to nutrient-rich topsoils (Huxtable et al., 2005; Windsor and Clements, 2001). Excessive nutrient availability and altered microbial communities in applied topsoil may have constrained recruitment for species sensitive to such changes (Brown et al., 2017; Scattini, 2008; White and Mullan, 2006).

Despite these limitations, species such as *Chrysopogon spicigerum* demonstrated successful establishment even under competitive conditions, indicating that some native grasses are capable of adapting to varied soil conditions when ecological requirements are met. These findings reinforce the importance of species-specific planning and support targeted site preparation—such as selective topsoil removal or soil amendment—to optimise recruitment for priority native grasses.

4.5. Slope gradient and soil surface preparation

In this study, slope gradient appeared to have minimal influence on vegetation establishment outcomes. Both trial sites exhibited comparable gradients (~12 %) and implemented similar erosion control strategies, including the construction of benches designed to stabilise the soil surface and enhance the retention of seeds and organic material during rainfall events (Machar et al., 2015; Witheridge, 2012). These measures likely mitigated the potential for slope-related variability in germination or seedling survival.

This finding is consistent with earlier work by Windsor and Clements (2001), who reported that slope and topographic position exert inconsistent effects on species establishment, often depending on site-specific conditions. While steeper slopes may increase erosion risk and reduce seed retention, their influence may be offset by appropriate engineering interventions and soil preparation techniques.

More critical to the success of seedling establishment in this study were surface preparation practices such as cross-ripping and shallow swale construction, both of which contribute to improved water infiltration, reduced surface runoff, and enhanced root penetration (Kim et al., 2022; Michael et al., 2019; Michael, 2010; Cole and Lunt, 2005). These practices promote microhabitats conducive to germination and early plant growth, particularly in sandy soils with low water-holding capacity.

Collectively, these results suggest that while slope gradient should

not be disregarded in rehabilitation planning, appropriate surface engineering and soil treatments are likely more influential determinants of successful direct seeding outcomes.

4.6. Project cost analysis

This study highlights the economic advantages of direct seeding relative to tubestock planting in mine site rehabilitation. The total cost of direct seeding for the 0.36 ha trial area was \$17,720.14, approximately 30 % less than the projected cost of \$25,569.05 for tubestock planting of canopy trees alone. Importantly, the direct seeding approach incorporated not only canopy species but also a broader suite of native grasses, shrubs, and subcanopy trees, thereby delivering more diverse vegetation outcomes at lower cost.

If the full species complement required for ecological rehabilitation were to be established via tubestock planting, total costs would likely be substantially higher due to the increased demand for nursery production, manual labour, irrigation, and maintenance. This aligns with findings from the broader restoration literature, where direct seeding has consistently been reported to reduce revegetation costs by 30–38 % while promoting greater genetic and structural diversity (Raupp et al., 2020; Sampaio et al., 2019; de Souza and Engel, 2018).

Despite these cost savings, the success of direct seeding remains highly dependent on environmental conditions, appropriate seed handling, and effective weed management. In this study, proactive management at the Native Vegetation Site resulted in successful establishment of native canopy species and regulatory target trees, while the Pasture Site demonstrated the risks of inadequate weed control. These outcomes reaffirm that while tubestock planting may deliver more immediate establishment for individual species, it is substantially more labour-intensive and less scalable than direct seeding, particularly for large and spatially complex rehabilitation projects (Sampaio et al., 2019; Grabau et al., 2011).

When implemented with tailored site preparation and adaptive management, direct seeding offers a cost-effective, scalable, and ecologically viable solution for mine rehabilitation in Southeast Queensland.

4.7. Limitations and future directions

This case study demonstrates the potential for direct seeding to meet regulatory rehabilitation targets under Queensland's Progressive Rehabilitation and Closure Plan (PRCP) framework, particularly for the re-establishment of native vegetation communities in post-mining landscapes. However, several limitations must be acknowledged when interpreting the results and considering their broader applicability.

First, the study was conducted at a single operational mine site on sandy-clayey soils, which limits the generalisability of the findings to other regions or substrate types. The absence of site replication also introduces the potential for pseudo-replication, constraining the robustness of site-wide inferences. Second, vegetation performance was assessed at two early post-seeding intervals (12 and 36 months), which capture short-term establishment dynamics but not longer-term outcomes such as species persistence, structural complexity, or ecological function.

Furthermore, although the study provides a comparison of cost projections between direct seeding and tubestock planting, it does not involve a direct, side-by-side implementation of both methods. As such, the economic assessment—while useful—is indicative rather than empirical. These limitations are consistent with the applied, site-specific nature of the trial but underscore the need for further research to refine and validate direct seeding approaches across broader contexts.

Building on these findings, several areas for future research and application are proposed:

- 1. Regional trials across Queensland:** Expanding direct seeding trials across diverse ecological zones, soil types, and mining operations would provide a more comprehensive understanding of success factors and support the development of region-specific best-practice guidelines.
- 2. Long-term ecological monitoring:** Extending monitoring to 5–10 years post-seeding would enable assessment of community composition, successional stability, and alignment with long-term PRCP goals.
- 3. Empirical cost comparisons:** Detailed, on-ground comparisons between direct seeding and tubestock planting—including inputs such as labour, seedling survival, maintenance, and irrigation—would provide a stronger basis for cost-benefit analysis.
- 4. Seed technology and delivery innovations:** Research into seed treatments, coatings, and alternative delivery methods could improve germination reliability, particularly for species with dormancy mechanisms or high sensitivity to environmental variability.
- 5. Policy integration and regulatory support:** Collaborating with regulators to embed direct seeding within PRCP policy frameworks could promote uptake, standardise expectations, and improve restoration outcomes at scale.
- 6. Scalable weed management strategies:** Developing cost-effective, site-adapted approaches to managing non-native vegetation—particularly in early successional stages—remains critical to improving establishment outcomes and reducing post-sowing maintenance burdens.

Taken together, these future directions highlight the growing relevance of direct seeding in mine rehabilitation and its potential to deliver scalable, ecologically aligned outcomes when supported by robust planning, targeted research, and policy innovation.

5. Key insights and practical applications

This study offers several practical insights for restoration practitioners and land managers aiming to meet rehabilitation objectives under Queensland's PRCP framework. First, the timing of direct seeding proved critical to establishment success. Sowing between February and April, following targeted surface preparation (e.g. cross-ripping and swale installation), supported effective germination and early growth—particularly for canopy species and some native grasses.

Second, the findings underscore the importance of careful site preparation. While topsoil application is often standard practice in mine rehabilitation, its use in this study may have limited native grass establishment due to altered nutrient profiles and microbial communities. These results suggest that physical soil treatments—such as slope profiling, controlled compaction, and selective topsoil removal—may in some cases offer more favourable conditions for native species recruitment than nutrient-enriched substrates.

Third, suppressing non-native biomass—particularly aggressive exotic grasses—emerged as a key determinant of restoration success. Where weed control was insufficient, native seedling establishment was significantly reduced. Targeted strategies such as increasing native sowing density, integrating early weed suppression treatments, and designing buffer zones between rehabilitated and pasture-dominated areas may enhance outcomes.

Direct seeding proved highly effective in achieving and exceeding canopy tree density targets (5200 vs. 600 stems/ha), offering a cost-efficient alternative to tubestock planting. However, these high densities also suggest the need for post-establishment thinning or active management to prevent overcrowding and ensure long-term structural and ecological functionality.

Finally, species-specific performance varied markedly, with grasses such as *Heteropogon contortus* and *Dichanthium sericeum* showing limited establishment. These outcomes point to the need for improved seed

handling, pre-treatment, and understanding of species-specific ecological requirements. Incorporating dormancy-breaking treatments and ongoing monitoring can improve recruitment success and inform future seed mix design.

Together, these findings reaffirm direct seeding as a viable and scalable strategy for ecological restoration in mine-affected landscapes, provided that it is supported by strategic site selection, targeted preparation, and adaptive management tailored to site and species conditions.

6. Conclusion

This study demonstrates that direct seeding, when implemented with careful site preparation and proactive weed management, can effectively achieve rehabilitation targets for post-mining landforms under Queensland's Progressive Rehabilitation and Closure Plan (PRCP) framework. While the findings are drawn from a single site and should be interpreted within the context of local conditions, they provide strong preliminary evidence that direct seeding can deliver both ecological and economic benefits in operational mine rehabilitation.

Rather than presenting definitive conclusions, this case study identifies key factors that influence the success of direct seeding—namely, species selection, seedbed preparation, suppression of non-native vegetation, and adaptive management. These insights offer a foundation for future research, including long-term monitoring, broader regional trials, and detailed cost comparisons with traditional revegetation methods.

By aligning observed outcomes with regulatory performance criteria, this study contributes practical knowledge to support the integration of direct seeding into standard rehabilitation practice. It highlights the method's potential to reduce costs, enhance species diversity, and increase scalability in mine site restoration. Continued research, innovation, and cross-sector collaboration will be essential to realising this potential and embedding direct seeding within sustainable land management frameworks across Queensland and beyond.

CRediT authorship contribution statement

Christopher D. Johnson: Writing – review & editing, Visualization, Resources, Methodology, Formal analysis, Conceptualization, Writing – original draft, Validation, Project administration, Investigation, Data curation. **Matthew Thomson:** Validation, Formal analysis, Writing – review & editing, Investigation, Data curation. **Michael Vermeulen:** Writing – review & editing, Project administration, Conceptualization, Supervision, Methodology. **Mark Waud:** Validation, Methodology, Writing – review & editing, Supervision, Formal analysis. **James McBroom:** Writing – review & editing, Methodology, Validation, Formal analysis. **Ruby N. Michael:** Validation, Methodology, Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

Christopher Johnson reports a relationship with Southern Pacific Sands that includes: employment. Matthew Thomson reports a relationship with Southern Pacific Sands that includes: employment. Michael Vermeulen reports a relationship with Southern Pacific Sands that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We acknowledge the Gubbi Gubbi peoples as the Traditional Custodians of the land where this research and fieldwork took place, and we pay our respects to Elders past, present, and emerging. We're grateful to David Francis and Steven Jarman for their early input into the

experimental design and methodology, and to Austin Jamieson, Meghan Hopper, and Alex Finney for their help with initial data collection. Thanks also to the anonymous reviewers for their constructive feedback, which helped strengthen this work.

Data availability

Data will be made available on request.

References

- Barron, P., Dalton, G., 1996. Direct seeding of native trees and shrubs in coastal environments. *J. Coast. Res.* 12 (4), 1006–1008.
- Brisbane City Council (BCC), 2015. Rhodes Grass. Weed Identification Tool. Viewed 6th June 2022. <https://weeds.brisbane.qld.gov.au/weeds/rhodes-grass>.
- Brown, S.L., Reid, N., Reid, J., Smith, R., Whalley, R.W., Carr, D., 2017. Topsoil removal and carbon addition for weed control and native grass recruitment in a temperate-derived grassland in northern New South Wales. *Rangeland J.* 39 (4), 355–361.
- Carr, D., et al., 2009. Improving direct seeding for woody crops in temperate Australia: a review. *Joint Venture Agrofor. Prog.* 9, 1–120.
- Chandrasekaran, M., Ashwath, M., Waggit, P., 2000. A Review of Revegetation Techniques in the Tropics. Supervising Scientist Report 333. Supervising Scientist, Canberra.
- Chenoweth EPLA and Bushland Restoration Services, 2012. South East Queensland ecological restoration framework: manual. In: Prepared on Behalf of SEQ Catchments and South East Queensland Local Governments, Brisbane.
- Chivers, I.H., Raulings, K.A., 2015. Australian Native Grasses: Key Species and their Uses, 4th ed. Native Seeds, Victoria.
- Clarke, S., French, K., 2005. Germination response to heat and smoke of 22 Poaceae species from grassy woodlands. *Aust. J. Bot.* 53 (5), 445–454. <https://doi.org/10.1071/BT04017>.
- Cole, I., Lunt, I., 2005. Restoring Kangaroo Grass (*Themeda triandra*) to grassland and woodland understoreys: a review of establishment requirements and restoration exercises in south-East Australia. *Ecol. Manag. Restor.* 6 (1), 28–33.
- Cole, I., Waters, C., 1997a. Pastures under adverse conditions – Handling what you have: Harvesting and sowing native grasses. In: Proceedings of the Twelfth Annual Conference of the Grassland Society NSW, 1997, pp. 95–103.
- Cole, I., Waters, C., 1997b. Harvesting and sowing native grasses. Grassland Society NSW. In: Proceedings 12th Annual Conference, pp. 95–103.
- Corbett, M.H., 1999. Revegetation of Mined Land in the Wet-Dry Tropics of Northern Australia: A Review. Supervising Scientist Report 150. Supervising Scientist, Canberra.
- Dalton, G.S., 1993. Direct seeding of shrubs and trees. In: A Manual for Australian Conditions. Primary Industries SA, Adelaide, South Australia, pp. 53–57.
- de Souza, D.C., Engel, V.L., 2018. Direct seeding reduces costs, but it is not promising for restoring tropical seasonal forests. *Ecol. Eng.* 116, 35–44.
- Department of Industry, Sciences, and Resources (DISR), 2016. Mine Rehabilitation: Leading Practice Sustainable Development Program for the Mining Industry. Australian Government. Retrieved from: <https://www.industry.gov.au/publications/leading-practice-handbooks-sustainable-mining/mine-rehabilitation>.
- Eyre, T.J., Kelly, A.L., Neldner, V.J., Wilson, B.A., Ferguson, D.J., Laidlaw, M.J., Franks, A.J., 2015. BioCondition: A Condition Assessment Framework for Terrestrial Biodiversity in Queensland. Assessment Manual. Version 2.2. Queensland Herbarium, Department of Science, Information Technology, Innovation and Arts, Brisbane.
- Farley, G.J., Bellairs, S.M., Adkins, S.W., 2013. Germination of selected Australian native grass species, with potential for minesite rehabilitation. *Aust. J. Bot.* 61 (4), 283–290. <https://doi.org/10.1071/BT12258>.
- Gibson-Roy, P., 2023. Limitations and successes for grassy community restoration: an Australian perspective. *Glob. Ecol. Conserv.* e02644.
- Gibson-Roy, P., Delpratt, J., 2015. The Restoration of Native Grasslands. Land of Sweeping Plains: Managing and Restoring the Native Grasslands of South-Eastern Australia, pp. 332–389.
- Gibson-Roy, P., Delpratt, J., Moore, G., 2007. Restoring the Victorian Western (Basalt) Plains grassland. 1. Laboratory trials of viability and germination, and the implications for direct seeding. *Ecol. Manag. Restor.* 8 (2), 114–122. <https://doi.org/10.1111/j.1442-8903.2007.00348.x>.
- Grabau, M.R., Milczarek, M.A., Karpiscak, M.M., Raulston, B.E., Garnett, G.N., Bunting, D.P., 2011. Direct seeding for riparian tree re-vegetation: small-scale field study of seeding methods and irrigation techniques. *Ecol. Eng.* 37 (6), 864–872.
- Gravina, A., McKenna, P., Glenn, V., 2011. Evaluating the success of mineral sand mine rehabilitation on North Stradbroke Island, Queensland: comparisons with reference eucalypt communities. *Proc. R. Soc. Queensl.* 117, 419–435.
- Grossnickle, S.C., Ivetić, V., 2017. Direct seeding in reforestation – a field performance review. *Reforestation J.* 94–142. <https://doi.org/10.21750/REFOR.4.07.46>.
- Huxtable, C., Koen, T., Waterhouse, D., 2005. Establishment of native and exotic grasses on mine overburden and topsoil in the Hunter Valley, New South Wales. CSIRO Publishing. *Rangeland J.* 27, 73–88.
- Kim, T.D.H., Yu, B., Srichandra, J., Low-Choy, S., Michael, R.N., 2022. Water flux and biomass production of native plants at different substrate compactions for landfill phytocaps in Southeast Queensland, Australia. *Ecol. Eng.* 183, 106745.
- Knight, A.J.P., Beale, P.E., Dalton, G.S., 1997. Direct seeding of native trees and shrubs in low rainfall areas and on non-wetting sands in South Australia. *Agrofor. Syst.* 39 (3), 225–239. <https://doi.org/10.1023/A:1005901111273>.
- Lodge, G.M., Whalley, R.D.B., 1981. Establishment of warm- and cool-season native perennial grasses on the North-West Slopes of New South Wales. I. Dormancy and Germination. *Aust. J. Bot.* 29 (2), 111–119. <https://doi.org/10.1071/BT9810111>.
- Machar S. Hardiman S. Trevitt L. & Featherstone D. 2015. Guideline for Batter Surface Stabilisation Using vegetation. Report to NSW Roads and Maritime Services.
- Mary Maher & Associates, 1994. Environmental Impact Statement Beachmere Sand Extraction Lots 162 and 163 Vol. 1.
- Mattiske, A., 2016. Mine Rehabilitation in the Australian Minerals Industry (An industry report commissioned by the Minerals Council of Australia).
- Michael, R.N., 2010. Landfill Phytocap Development and Performance Evaluation Using Australian Native Plants. PhD thesis. The University of Melbourne, Department of Civil and Environmental Engineering & School of Botany.
- Michael, R.N., Yu, B., Wintle, B.A., Doronila, I.A., Yuen, S.T.S., 2019. The effect of substrate compaction on plant water use and the implications for phytocap design specifications. *Ecol. Eng.* 127, 195–203. <https://doi.org/10.1016/j.ecoleng.2018.11.023>.
- Mott, J.J., 1978. dormancy and germination in five native grass species from savannah woodland communities of the Northern Territory. *Aust. J. Bot.* 26 (5), 621–631. <https://doi.org/10.1071/BT9780621>.
- Northern Yorke Natural Resources Management (NYNRM), 2011. Direct seeding. Northern and Yorke NRM Plan. Fact Sheet No. 4. June 2011.
- NSW Mining, 2014. Improving Rehabilitation through Farming Techniques at Coal & Allied. Coal & Allied.
- Palmerlee, A.P., Young, T.P., 2010. Direct seeding is more cost effective than container stock across ten woody species in California. *Native Plants J.* 11 (2), 89–102. <https://doi.org/10.2979/npj.2010.11.2.89>.
- Piggott, J.P., Brown, P.H., Williams, M.M., 1987. Direct Seeding Trees on Farmland in the Western Australian Wheatbelt. Report 146. Department of Agriculture and Food, Western Australia.
- Pinkard, L., 1992. Ecological Impediments to the Establishment of Trees by Direct Seeding on Pastoral Sites in the Midlands of Tasmania.
- Pryde, E.C. and Duncan, D.H. 2015. Monitoring and assessment of direct seeding revegetation projects in the Goulburn Broken CMA: a Report to the Goulburn Broken Catchment Management 1–48.
- Queensland Herbarium, 2023. Regional Ecosystem Description Database. Version 13. May 2023. Department of Environment & Science, Brisbane.
- Ralph, M., 2009. Growing Australian Native Plants from Seed. Bushland Horticulture Publications, Victoria Australia. ISBN: 978-0-646-42866-6.
- Raup, P.P., Ferreira, M.C., Alves, M., Campos-Filho, E.M., Sartorelli, P.A.R., Consolaro, H.N., Vieira, D.L.M., 2020. Direct seeding reduces the costs of tree planting for forest and savanna restoration. *Ecol. Eng.* 148, 105788.
- Sampaio, A.B., Vieira, D.L., Holl, K.D., Pellizzaro, K.F., Alves, M., Coutinho, A.G., Schmidt, I.B., 2019. Lessons on direct seeding to restore Neotropical savanna. *Ecol. Eng.* 138, 148–154.
- Scattini, W., 2008. Factsheet - Queensland Bluegrass. Pastures Australia.
- Scheltema, M., 1993. Direct Seeding of Trees and Shrubs. Greening Western Australia, Fremantle.
- Simple, W., Koen, T., Cole, I., 1999. Establishing native grasses in degraded pastures of Central Western New South Wales. *Rangeland J.* 21 (2), 153–168.
- Smith, P., Nichols, O.G., 2011. Development and assessment of rehabilitation criteria for high dune mineral sands mining on North Stradbroke Island. Submitted to. *Proc. R. Soc. Queensl.* 117, 347–364.
- Southern Pacific Sands, (SPS), 2023. Progressive Rehabilitation Closure Plan - Planning Part.
- Spain, C.S., Nuske, S.J., Gagen, E.J., Purtill, J., 2025. Evaluating native ecosystem rehabilitation options in Queensland: Technical Paper. Office of the Queensland Mine Rehabilitation Commissioner, Queensland Government, Brisbane.
- Stokes, Z., 2010. Fact Sheet No5: Revegetation Direct Seeding. Planning Revegetation on Farms in the South East. Natural Resources South East, pp. 60–64.
- Turner, S.R., Cross, A.T., Just, M., Newton, V., Pedrini, S., Tomlinson, S., Dixon, K., 2022. Restoration seedbanks for mined land restoration. *Restor. Ecol.* 30, e13667. <https://doi.org/10.1111/rec.13667>.
- Wagner, M., Pywell, R.F., Knopp, T., Bullock, J.M., Heard, M.S., 2011. The germination niches of grassland species targeted for restoration: effects of seed pre-treatments. *Seed Sci. Res.* 21 (2), 117–131. <https://doi.org/10.1017/S0960258510000450>.
- White, P., Mullan, G., 2006. Revegetation Techniques and Timelines. Department of Environment and Conservation. Australian Government.
- Wilson, P.R., Taylor, P.M., 2012. Land Zones of Queensland. Queensland Herbarium, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane, p. 79.
- Windsor, D.M., Clements, A., 2001. A germination and establishment field trial of *Themeda australis* (Kangaroo grass) for mine site restoration in the Central Tablelands on New South Wales. *Restor. Ecol.* 9 (1), 104–110. <https://doi.org/10.1046/j.1526-100X.2001.009001104.x>.
- Witheridge, G., 2012. Erosion and Sediment Control – A Field Guide for Construction Site Managers. Catchments & Creeks Pty Ltd, Brisbane. Queensland.
- Woodall, G., 2014. Systems Approach to Reliable Direct Sowing of Native Plants: Implications for the Revegetation of Mined and Agricultural Landscapes, Powerpoint Presentation. University of Western Australia.
- Zamin, T.J., Jolly, A., Sinclair, S., Morgan, J.W., Moore, J.L., 2018. Enhancing plant diversity in a novel grassland using seed addition. *J. Appl. Ecol.* 55 (1), 215–224. <https://doi.org/10.1111/1365-2664.12963>.