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Harnessing ecological processes in the Ranger Uranium Mine revegetation strategy

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Abstract

Energy Resources of Australia Ltd's (ERA) Ranger Uranium Mine, surrounded by Kakadu National Park (KNP) in Australia's Northern Territory, ceased mining in 2012 after 31 years of operation. All rehabilitation activities, including revegetation, shall be completed by 2026, followed by a post-closure monitoring and maintenance period. A detailed Mine Closure Plan for Ranger was published online in 2018 and will be updated annually (Energy Resources of Australia Ltd & Eco Logical Australia [ERA & ELA] 2018).

At ERA Ranger Mine, the final landform made of waste rock will be revegetated using local native species to establish a self-sustaining ecosystem, similar to the eucalypt savanna woodlands that dominate the adjacent area of the KNP. The waste rock substrate dictates fairly harsh conditions, with high temperatures, irradiance and surface reflectance, relatively low water holding capacity (at least until weathering and other soil development processes progress), and low or no soil organic matter, microbial activity or nutrients. Together with the long dry seasons in the monsoonal wet–dry tropics, and the high fire frequencies in the KNP, this poses great challenges for the Ranger mine's ecosystem restoration.

Taking into account the above challenges and based on the learnings from extensive studies and revegetation trials at Ranger over the last three decades undertaken by ERA and other research agencies (e.g. CSIRO, ERISS), a revegetation strategy was developed and endorsed by key stakeholders in 2004. Following this, ongoing research and monitoring of the revegetation established by applying this strategy has continued to develop the science underpinning this strategy.

*The revegetation strategy is to initially establish framework overstorey species, or K-strategists (*sensu *MacArthur & Wilson 1967), along with a subset of important and reliable midstorey and understorey species. These species form the 'framework' for the ecosystems, controlling much of a site's nutrient and water resources, providing many of the core habitat values for other plants and animals, and contributing substantially to both the overall functioning and long-term stability of the plant communities.*

As the initial plantings establish and develop, a process expected to take five or more years based on trial landform experience, the soil and litter layer will develop, canopy should increase providing shade, and plants will develop attributes resilient to fires (e.g. stem diameter, lignotubers). It is at this stage that introductions of additional species are planned to improve the composition and structure of the ecosystem. These species are generally those that risk being too competitive or, alternatively, too sensitive to introduce at the earlier (initial) stage.

This two-stage approach to species establishment harnesses ecological processes such as vegetation community and soil development, and species-specific environmental preferences, to underpin the Ranger revegetation strategy. Well-intended aspirations to introduce all target species at the initial revegetation establishment stage should defer to an appreciation of ecological processes that will increase the likelihood that revegetation efforts will result in success. Ongoing planning, research, monitoring and adaptive management should ensure the best possible revegetation outcome at Ranger mine.

This paper reviews the natural ecological processes that govern the eucalypt-dominated ecosystems of the region and discusses the current Ranger revegetation strategy and its validation by a 10-year-long ongoing field test on the Ranger trial landform. The trial landform studies have demonstrated that the key overstorey *species of the target vegetation communities can establish and mature on the waste rock substrate. Current research is focused on the establishment of understorey species.*

Keywords: *revegetation strategy, framework species, tropical woodland, uranium mining, waste rock*

1 Introduction

Energy Resources of Australia Ltd's (ERA) Ranger Uranium Mine, surrounded by Kakadu National Park (KNP) in Australia's Northern Territory, ceased mining in 2012 after 31 years of operation and is currently processing remaining ore, relocating tailings into the mined-out pits, backfilling pits and constructing the final landform (Figure 1). All rehabilitation activities, including revegetation, shall be completed by 2026, followed by a post-closure monitoring and maintenance period. A detailed Mine Closure Plan (MCP) for Ranger was published online in 2018 and will be updated each year until closure is complete (ERA & ELA 2018).

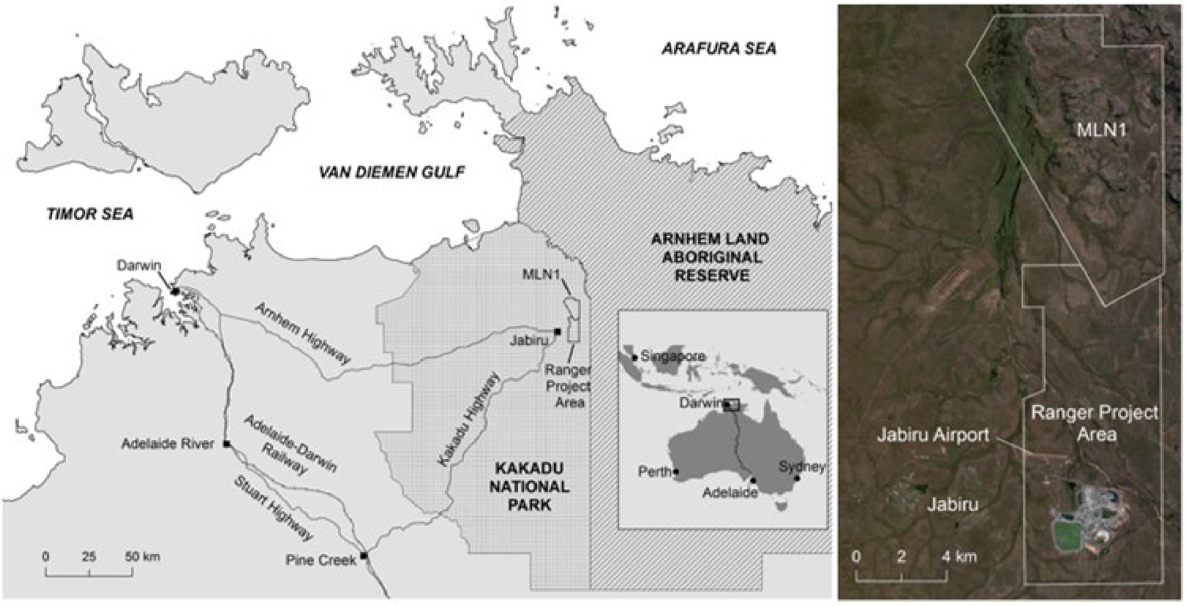

Figure 1 Location of Ranger Uranium Mine in the Northern Territory of Australia

The revegetation objective for ERA Ranger Mine is stated in the *Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine* (Department of the Environment and Energy 1999), which sets out the overarching environmental management at Ranger (referred to as the Environmental Requirements [ERs]). The primary ER relevant to revegetation is ER clause 2.2(a):

> *"Revegetation of the disturbed sites of the Ranger Project Area using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu National Park, to form an ecosystem the long term viability of which would not require a maintenance regime significantly different from that appropriate to adjacent areas of the park."*

During the course of mining operations, approximately 950 ha of land has been disturbed and 127 Mt of waste rock has been stockpiled at the site (ERA & ELA 2018). This material is being used to backfill the pits and construct a 760 ha final landform that is designed to be compatible with the surrounding landscape. The three main rock types in Ranger waste rock stockpiles are primary, weathered and laterite materials. Primary material consists of unweathered host rock, which largely consists of altered quartz-feldspar schists and to a lesser extent cherts and carbonaceous materials. Weathered material consists of friable rock (usually quartz-feldspar schist) with altered mineral assemblages, but generally still low in clay content. Laterite is a near surface, highly weathered and sometimes reconsolidated material that is generally high in iron and aluminium clays and other gangue minerals (ERA & ELA 2018).

There is little or no topsoil or alternative materials available, or particularly suited, to construct the final landform. Experience with mixing waste rock with laterite for revegetation at Ranger has generally resulted in high weed loads and substandard rehabilitation (Daws & Gellert 2011; Reddell & Zimmermann 2002). Thus waste rock alone will be used.

Decades of research, and more recent work on a large-scale trial landform (TLF), have demonstrated that most key overstorey species of the target vegetation communities can establish and mature on a waste rock substrate. In the highly porous waste rock substrate, plant available water (PAW) is a key constraint to revegetation success. Data analysis and modelling have demonstrated that sufficient PAW will be present in the constructed landform to support the evapotranspiration demand of a mature, eucalypt-dominated ecosystem (Lu et al. 2019; Segura 2017). A key determinant of PAW is the proportion of fines in the substrate; this will increase, and PAW will improve, due to weathering of the waste rock over time, generation and illuviation of organic matter (roots and litter), and the activity of invertebrates and microbial organisms.

The waste rock substrate dictates fairly harsh initial conditions, with high temperatures (around 50°C), irradiance and surface reflectance, relatively low water holding capacity (at least until weathering and other soil development processes progress), and low or no soil organic matter, microbial activity or nutrients (Huang & You 2018; Lu 2017; Lu et al. 2019).

The natural ecological processes that govern the eucalypt-dominated ecosystems of the region are reviewed below, and discussed in terms of the Ranger revegetation strategy (ERA & ELA 2018). Some key findings from a 10-year-long field test of the revegetation strategy are presented.

2 Reproductive ecology of northern Australian eucalypt savanna woodlands

Eucalypt-dominated savanna woodlands and forests cover the great majority of northern Australia (Boland et al. 1992). Such a broad distribution throughout the wet–dry tropics is controlled predominantly by three factors (Williams et al. 1996): (1) underlying geomorphology, which influences site hydrological features and soil fertility; (2) seasonality and predictability (inter-annual variability) of climate; and (3) frequency and intensity of disturbance events, especially fires.

These factors govern the structural complexity (e.g. height, biomass, number of strata, size class distributions, root depth and distribution patterns), species composition and the functioning of the vegetation (e.g. water use, nutrient uptake, regeneration strategies, phenology) (Reddell & Meek 2004). Where water is not the limiting factor, vegetation patterns generally follow soil nutrient gradients (Florence 1981).

Plant adaptations reflect the environmental conditions in which they evolved and the disturbance regime is the key natural selection influences in the evolution of northern Australian vegetation, for example, fire, cyclones and wet–dry seasonality. The plants of these communities fall into two groups based on their reproductive strategy: K-strategists (long-lived plants with low reproductive rates) and r-strategists (short-lived plants with high reproductive rates) (MacArthur & Wilson 1967).

Plants exhibiting a K-strategy, or sprouters (Whelan 1995), include all the long-lived, framework species in the eucalypt savanna woodlands or forests, and rely on an ability to resprout from lignotubers and root suckers (Fensham & Bowman 1992; Lacey & Whelan 1976; Ward et al. 1997). Although they produce and shed seed, seedling regeneration is considered rare in *Eucalyptus tetrodonta* and *E. miniata* (Fensham 1992). The chance of an individual seedling surviving by the end of the first dry season is extremely low, considering their slow growth and the combined pressures of a lack of water and the likelihood of fire. In their review of previous revegetation research at Ranger mine, Reddell & Zimmermann (2002) noted that, of 5,000 young seedlings of framework species observed in natural woodland plots, not one survived after two years. Other research in north Australian eucalypt savannas has found that seedlings of *E. miniata* and *Acacia oncinocarpa* grown from seed were reduced by 75% and 65% respectively by the end of the first dry season, and this had further dropped to only 11% and 33% survival by the middle of the following dry season (Setterfield 2002). In contrast, woody resprouts of framework species are common components of the ground and understorey layer of these communities. These sprouts arise from subterranean lignotubers and are resilient to the harsh dry season conditions, including the frequent low-intensity fires that are a major disturbance in the northern savannas.

Some K-strategy species, such as eucalypts, can resprout from relatively small pieces of root, rhizomes or lignotubers (Fensham 1992). While most eucalypts with the ability to resprout from roots do so from shallow rhizomes, *E. tetrodonta* is unique in that it is able to resprout from lateral roots (Brooker & Kleinig 1994). An extensive root system is also important in most plants with limited nutrient and water resources, and is further enhanced by the existence of a lignotuber. The benefits of below-ground biomass, including lignotubers, are more important to young plants. The temperature gradient generated by a fire decreases with increasing tree height above-ground (Whelan 1995). Thus, once plants reach a minimum height, say around 2 m (Andersen et al. 2005), they escape destruction of their above-ground stems caused by a typical Top End fire and will be able to emerge from the fire-suppressed understorey.

Plants with an r-strategy are typically short-lived plants with high reproductive rates, and include the majority of ground-storey grasses and herbs as well as some short-lived shrubs and trees, such as acacias and grevilleas. These species generally rely on seed for reproduction and develop a soil seed bank (Ward et al. 1997). This strategy is based on the ability to rapidly colonise a disturbed area and capture the resources made available by the disturbance. The frequency and intensity of fire have a major effect on the composition of r-strategists that capture a disturbed site (e.g. Andersen et al. 1998; Fensham & Bowman 1992; Grant & Loneragan 2001; Lonsdale & Braithwaite 1991; Williams et al. 2003). Such species do not contribute significantly to ecosystem stability, but provide important habitat and food resources for fauna. Most natural disturbances, such as fire, predominantly affect above-ground biomass, favouring long-lived, framework K-strategists that have persistent below-ground structures. Unnatural disturbances, including mining, that destroy these below-ground structures, remove the competitive advantage and ability to persist of these species. Rehabilitation of mined-out ecosystems will not be able to utilise the resilient features of framework species, but must reinstate these features through facilitating recolonisation and development from seed. The most important aspects of the establishment of framework species from seed or seedlings are: (1) protection from fire, while below-ground structures develop; and (2) minimal competition from faster-growing, r-adapted plants (these are discussed further below). Until the resilience of framework species is reinstated, the successful long-term development of rehabilitation is less likely.

3 The Ranger revegetation strategy

The Ranger revegetation strategy was first endorsed in 2004 (Reddell & Meek 2004) and more recently refined and published in the MCP (ERA & ELA 2018). The strategy harnesses the ecological processes that shape the natural ecosystems of the region, particularly the reproductive ecology and the concept of framework species as discussed above, to increase the likelihood of a successful rehabilitation outcome.

The strategy comprises 14 elements that address setting objectives and targets; understanding site physical and chemical constraints; species selection and target densities; site preparation and soil amendments including microbial inoculants; plant establishment methods including fertiliser use and irrigation; seed management; weed and fire management; and ongoing monitoring.

3.1 Element 1: Develop different revegetation strategies for different land surface types

The physical, chemical and biological characteristics of the waste rock landform and disturbed natural areas with a 'soil' layer are fundamentally different to each other and also the natural ecosystems of the region. Despite this, they share a broad objective of re-establishing vegetation that is similar to the natural eucalypt-dominated woodlands, or other suitable vegetation communities of the surrounding area. To achieve this from such different starting points requires specially tailored revegetation strategies and the revegetation will develop along different pathways, or trajectories, to become the mature target ecosystem/s (which will also vary depending on the constraints of the substrates).

The waste rock landform presents unique ground conditions that are not present in the natural environment and subsequent elements of this revegetation strategy are largely focused on addressing inherent challenges such as limited PAW, high levels of irradiance, surface reflectance and open space, threat of weeds and fire, and an initial absence of any plants, propagules, organic matter, nutrient cycling, or natural fauna or microbial communities. While the disturbed natural land with soil has more suitable physical and chemical characteristics for vegetation establishment compared to bare waste rock, it still requires a revegetation strategy that will overcome its own unique challenges. These include the threats of 'weeds' (including local native aggressive *Acacia* spp. and annual spear grass (*Sorghum* spp.)), fire, herbivores and competition for resources from surrounding vegetation, which necessities adjusted strategies such as spray of pre-emergence herbicides, more frequent weed and fire management and revegetation maintenance interventions (e.g. thinning of aggressive acacias).

3.2 Element 2: Identify the likely physical and chemical constraints of the final landform that will influence both the initial establishment and the long-term growth, development and functioning of revegetated plant communities

This element concentrates on characterising geomorphic and hydrological features, in different facets of the rehabilitation, that will determine (a) seasonal water availability for vegetation (e.g. infiltration and PAW), and (b) chemical fertility and any potential phytotoxicity in the varying substrates.

ERA's water balance study of the Ranger trial landform indicates that a waste rock cover layer of 4–6 m thick would provide sufficient PAW for revegetation (Lu et al. 2019). Although framework tree and some shrub roots are capable of accessing deeper rock substrates (up to 6 m), low net PAW in the near surface section (e.g. 0–2 m) may affect the initial establishment of the overstorey vegetation and long-term success of shallower rooting species. Evidence from the trial landform indicates that surface and subsurface preparation methods such as rip lines and consolidation of sections of the subsurface as a result of material placement methods will improve the water holding capacity of the waste rock substrate.

Many soils typical of the tropical north of Australia are very old and highly leached, and have inherently low fertility, including a particularly low phosphorus and nitrogen content (Langkamp & Dalling 1979). Compared to local natural soils, Ranger mine waste rock has been found to have higher pH, higher content of labile minerals and consequently higher concentration of plant nutrients and other elements, though lower total N (Table 1; Fitzpatrick et al. 1989; Gellert 2014). Huang & You (2018) found that nutritional and microbial components of the TLF waste rock 'soil' are developing; however, they observed relatively low rates of mineralisation that may be due to heat stress, rapid evaporation and water deficit at the surface. As vegetation establishes, and overstorey canopy and shade from other plants increase, these conditions should improve.

There is no concern of phytotoxity limiting revegetation outcomes. As part of a 2018 cumulative ecological risk assessment, Bayliss (2018) determined that the risk to revegetation from mine-derived chemicals is assumed to be zero. This is supported by observations and studies of vegetation irrigated with water (mostly waste rock solutes) for over a decade, which indicate there are no observed negative effects on vegetation from waste rock contaminants (e.g. Addison 2011).

3.3 Element 3: Maximise surface roughness and 'patchiness' during site preparation

The aim is to establish a land surface that has (a) localised run-on/runoff zones for control and capture of sediment, water and nutrients, and (b) microhabitats for seedling establishment and litter accumulation/decomposition, to encourage natural flora recruitment and ground dwelling fauna. Surface ripping has been identified as critical to early erosion control and subsequent vegetation establishment and soil development (e.g. Saynor et al. 2019). Rip lines of 0.5 m depth will be installed at 4 m intervals across the entire surface of the waste rock landform.

Table 1 Chemical analysis of waste rock substrate at trial landform (TLF) and soil at reference woodland sites

Parameter	TLF waste rock	Reference sites	Parameter	TLF waste rock	Reference sites
Moisture (%)	0.5 (±0.1)	0.5 (±0.1)	Paste NH_3-N (mg/kg)	0.07 (±0.01)	1.27 (±0.30)
Paste pH	8.0 (±0)	6.3 (±0.1)	Total N (mg/kg)	45.1 (±14.0)	422 (±20.5)
Paste EC (µS/cm)	260 (±49.2)	14.4 (±2.2)	Ca (mg/kg)	85.8 (±23.8)	0.8 (±0.1)
P (ppm)	410 (±6.6)	0.2 (±0.1)	K (mg/kg)	20.3 (±1.9)	4.9 (±0.0)
Total P (mg/kg)	460 (±25)	64.8 (±12.6)	Mg (mg/kg)	61.7 (±18.3)	BDL
Total S (%)	0.03 (±0.02)	0.02 (±0.01)	Na (mg/kg)	17.0 (±3.8)	1.2 (±0.1)
NO_2-N (mg/kg)	BDL	0.28 (±0.05)	CEC	5.3 (±0.5)	3.2 (±0.2)
NO_3-N (mg/kg)	0.64 (±0.48)	0.24 (±0.08)	Al (me/100 g)	0.4 (±0.1)	1.8 (±0.1)

BDL = below detection limit

3.4 Element 4: Identify and describe vegetation types that are ecologically and technically realistic target endpoints, for different facets of the final landform, based on the likely physical and chemical environments that will be created

The waste rock substrate of the final landform has no exact analogue in the surrounding environment, yet will largely dictate what final revegetation will be achievable. The identification of suitable reference vegetation types has therefore mainly focused on areas in the surrounding natural landscapes that have the most similar geomorphic characteristics to those of the final landform (based on the reasonable assumption that many of the environmental determinants of vegetation composition and distribution will be similar in these settings). The identified suitable reference vegetation is generally a mixed or dry open Eucalyptus-dominated woodland and, based on experience, ERA are confident that this revegetation can be established.

The revegetation strategy is to initially establish framework overstorey species along with a subset of important and reliable midstorey and understorey species. Framework species control much of a site's nutrient and water resources, providing many of the core habitat values for other plants and animals, and contributing substantially to both the overall functioning and long-term stability of the plant communities (Reddell & Hopkins 1994). They typically include *Eucalyptus* spp., *Corymbia* spp., *Xanthostemon* spp., ironwood (*Erythrophleum chlorostachys*), *Terminalia* spp., quinine bush (*Petalostigma* spp.) and other long-lived shrubs. Ecologically, these species are characterised by:

- High resistance to (tolerance of) fire.
- Reliance primarily on vegetative regeneration strategies (through root suckers, lignotubers and rhizomes) in response to stresses and disturbance.
- Seeds that are relatively short-lived and do not accumulate as a canopy (serotinous) or soil seed bank.
- A population structure dominated by even-age cohorts from one or a small number of discrete regeneration/recruitment events (usually from vegetative sprouts), resulting in highly discontinuous size class distribution.
- High predictability of growth performance and development.

3.5 Element 5: Use of seed collected within KNP for all species

The use of seed collected from KNP ensures that the genetic make-up of the revegetation is consistent with local populations or 'provenances' of each individual species and provides a buffer for adapting to future global change. This commitment is also consistent with the wishes of Traditional Owners for the area.

3.6 Element 6: Introduce a range of local mycorrhizal fungi to aid in the establishment of the framework species

Most woodland species have a positive association with mycorrhizal fungi, which act to alleviate nutritional deficiencies (especially nitrogen and phosphorus) (Reddell & Milnes 1992). An effective microbial population, including mycorrhizae, is considered essential to establishing a self-sustaining woodland ecosystem on waste rock. An effective method has been refined at Ranger mine by incorporating mycorrhizal fungal spores in the tubestock potting mix during propagation in the nursery.

3.7 Element 7: Include non-aggressive local native acacias but avoid the use of high densities of aggressive Acacia species

A number of *Acacia* species are common in the local woodlands, and are generally a positive component of the revegetation because of their ability to fix atmospheric nitrogen and rapidly produce organic matter. However, some acacias can be overly 'aggressive' in young revegetation and outcompete the slower-growing framework species, which are much less competitive until they have established underground regenerative structures (e.g. Meek 2008; Zimmerman & Reddell 2011). Only natural densities of short-statured, non-aggressive acacias will be included at initial establishment. Other *Acacia* species are expected to self-colonise over time or can be introduced at the secondary establishment stage, once the framework species are dominating the site (see Element 8 below).

3.8 Element 8: Avoid actively introducing overly competitive grasses and herbaceous species, or sensitive midstorey species, until framework species are established and conditions are suitable.

In young revegetation, vigorous grasses and herbaceous species can outcompete the preferred framework species (as for acacias) and if present in high densities can also increase the risk of fire (e.g. Meek 2008). Only low-risk native grasses and herbs will be introduced at initial establishment.

As the initial plantings establish and develop, a process expected to take five or more years based on trial landform experience (ERA & ELA 2018), the soil and litter layer will develop, canopy should increase providing shade and plants will develop attributes resilient to fires (e.g. stem diameter, lignotubers). It is at this stage that introductions of the remaining target understorey (and any midstorey or overstorey) species are planned to complete the diversity of the ecosystem. These species are generally those that are either too high risk or, alternatively, too sensitive to introduce at the earlier (initial) stage.

High risk species, also known as r-strategists (sensu MacArthur & Wilson 1967), are those that have, for example, high fecundity and rapid growth and should thrive in the temporary initial conditions of open space and high sunlight. These species might threaten to take advantage of the situation and outcompete the preferred eucalypt and other framework species as they gradually mature. This group includes aggressive acacias, grasses and some herbs and will only be introduced during the secondary establishment stage. This will ensure that the preferred species are dominating the ecosystem and the r-strategists can establish in natural densities that will be supportive of a stable, self-sustaining ecosystem.

Sensitive species are those that are not suited to initial conditions; however, they should be suited to passive or active introduction as environmental conditions improve. For example, *Xanthostemon paradoxus* is an important midstorey tree species and has shown extremely low survival rates in past revegetation at ERA. Research conducted in 2011–2012 investigated the potential reasons for this and tested planting methods that could be used to improve the survival rate of this species in future revegetation (Gellert 2012). This study demonstrated that the use of shadecloth tree shelters when planting may significantly increase survival, likely because the shadecloth reduced the light stress and heat stress experienced by the plants during planting shock and initial establishment.

More recently, Parry (2018) found that understorey species established from seed at almost twice the rate in the presence of surface litter as compared to other ameliorants (fine sand, fertiliser, ground incorporated organic matter, or combinations) or controls. Relationships between seedling emergence and distance to nearest tree, canopy cover, and seed mass were also found. The study concluded that when establishing native understorey on mine waste rock in hot and intermittently dry periods in the wet season, the application of surface litter to waste rock with broadcasted seed may improve seedling establishment. With understorey species that have poor establishment from seed, tubestock planting has been proved to be a viable method for more efficiently introducing native understorey species into the ecosystem (Parry 2018).

These species will be established through either application of seed or tubestock planting, potentially concentrated in islands or strips across the final landform (particularly for the more infrequent or recalcitrant species). These concentrated areas will act as sources of future propagules which will radiate out and self-colonise the rest of the landform over time. The work will be scheduled to utilise wet season rain and will be complemented by a broadscale application of suitable fertiliser to assist early establishment and also contribute to the overall nutrient status of the developing rehabilitation.

3.9 Element 9: Use nursery-grown planting stock to establish the framework species

Based on current technology this will (a) significantly reduce the risk of planting failure associated with erratic rainfall and extreme temperatures; (b) accelerate the speed of vegetation development; and (c) overcome the poor predictability of establishing a final revegetated landform from direct seeding techniques. This strategy is proven to be the most cost-effective method for the initial establishment of framework species and is reasonable given the constraint imposed by greatly limited seed availability within KNP. However, where reliable and predictable direct seeding success can be achieved for some species, such as kapok (*Cochlospermum* spp.) and emu apple (*Owenia vernicosa*), this method will be used.

3.10 Element 10: Apply fertilisers in a strategic manner using formulations and delivery methods that maximise their effectiveness

Slow release fertiliser will be incorporated into the potting media for all planting stock, at rates that provide a significant ‘residual’ effect on growth after planting out. Some fertiliser will also be applied during the first wet season to facilitate more rapid seedling growth, especially if direct seeding is used; however, this fertiliser will not be of a highly soluble formulation. Additional fertiliser will be applied as required to ensure vegetation structural development is not inhibited and that sufficient site nutrient recapitalisation occurs, and also to support any subsequent infill or understorey planting. Fertilisation particularly favours invasive grassy species colonisation in the Top End and will need to be carefully managed to minimise this risk.

3.11 Element 11: Provide irrigation to seedlings at initial establishment

For the initial planting activities, irrigation shall ensure good plant survival rates across all framework species during dry season and potentially erratic wet season conditions. However, irrigation will only be applied for six months or so, to avoid dependence and encourage deep rooting. Where possible, wet season rains will be used as the primary water source, particularly for the replacement and secondary planting activities.

3.12 Element 12: Rigorously control potentially threatening weed species

Weeds are the most critical risk to the reconstruction of the ecosystem. Final landform substrates shall be carefully managed during construction to prevent site contamination with weeds or their seeds. Furthermore, a weed-free buffer zone (approximately 200 m wide) around the revegetation sites will be established to assist in preventing weed incursion into revegetation zones and areas will be treated with a pre-emergence, residual herbicide prior to planting. Weed monitoring and treatment will continue during the revegetation and post-closure management phases until completion criteria and relinquishment are achieved.

3.13 Element 13: Exclude fire from the revegetation areas during the first five to eight years after establishment

Dependent on the stage of development in the revegetation (e.g. framework species achieving a minimum diameter of 6 cm), low-intensity fire could be introduced in years 5–8. Fire would be used to reduce fuel loads and to prime the framework species composition and structure to future fire regimes. However, due to the low quantity of fine 'soil' material and organic matter at the surface of the waste rock substrate, it is unlikely a substantial amount of understorey, thus fuel, would be established in years 5–8, based on observations on the trial landform. Therefore, fire will only be introduced once the secondary species introductions are complete, all plants have reached adequate maturity, and grasses are present to support an effective controlled burn.

3.14 Element 14: Design and implement a rigorous and scientifically based strategy for ongoing evaluation of the performance of the revegetation

ERA is committed to a period of post-closure management, including all monitoring, maintenance and other activities required to manage the rehabilitated site, until all closure criteria can be satisfied and a close-out certificate is obtained (ERA & ELA 2018).

A flora and fauna monitoring program will be developed for rehabilitation and closure, taking into consideration the information provided by the monitoring of natural reference sites. The monitoring program will comprise vegetation plots and fauna trapping transects to address terrestrial flora and fauna.

The monitoring program will capture relevant information as the revegetation progresses. For example, in the initial stages of revegetation (e.g. years 1–5), the flora monitoring will focus on species survival rates, which will inform remediation works. As saplings develop, a more comprehensive suite of parameters addressing ecosystem development and closure criteria will be introduced. The early fauna monitoring (e.g. years 1–3) is likely to focus on incidental observations of vertebrates and invertebrates. As the vegetation establishes, there will be an increase in monitoring to include trapping and systematic observation-based surveys to determine the presence of major functional groups. The proposed survey frequency of flora and fauna across the final landform is: three, six and 12 months (year 1); annually (years 1–5); and one-off surveys every five years (e.g. at years 10, 15, etc.).

4 A 10-year-long ongoing field test of the revegetation strategy

4.1 Study description

The above Ranger revegetation strategy has been tested and refined by a large-scale field experiment, namely the Ranger trial landform (TLF) that was constructed in 2008 to 2009. The 8 ha TLF design incorporated treatments to allow testing of the performance of different types of substrates over the waste rock base, different substrate thicknesses over the waste rock base (2 m and 5 m thick), different planting methods (direct seeding and tubestock) and different irrigation regimes (irrigated and non-irrigated) (Figure 2). The substrates included in the TLF were: waste rock only; and waste rock blended with 30% volume/volume of laterite material. Note that since then the laterite mixing is no longer an option and the proposed final landform will be predominantly constructed with waste rock only (ERA & ELA 2018). The white section shown in Figure 2 represents the 50 m wide area that was never irrigated. The TLF was constructed with a 2% slope and was ripped at 2 m intervals.

The TLF stands 4–7 m above the original natural ground surface and was constructed using 800,000 tonnes of primary waste rock and some weathered material (Daws & Poole 2010). Photos of the primary material and weathered rock used for construction of the TLF are shown in Figure 3. Areas 1A and 3 were first planted in March 2009 with a total of 4,690 tubestock using 41 locally harvested native species (Daws & Poole 2010), comprising midstorey and overstorey species, which were planted mainly between March and July 2009 (Figure 4).

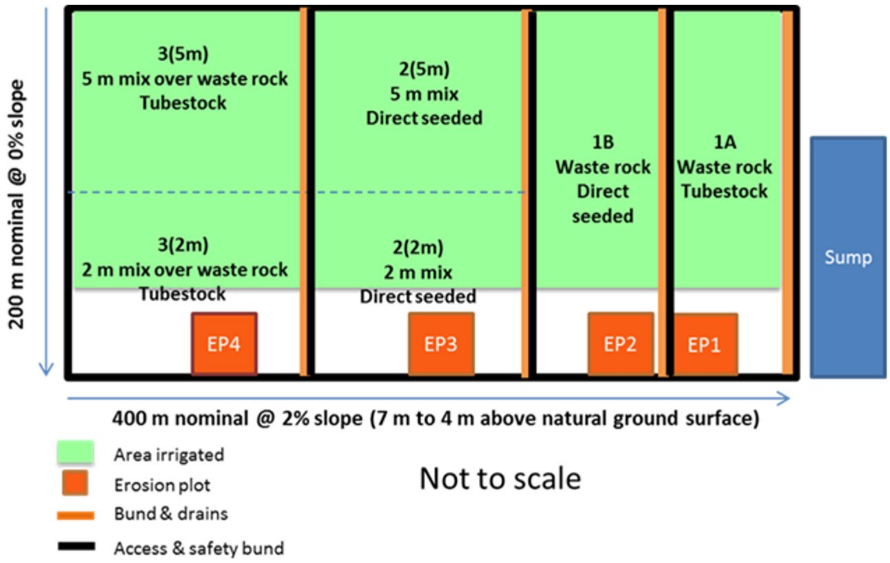

Figure 2 Ranger trial landform layout

Figure 3 Rock types used to construct the trial landform

Figure 4 Ranger trial landform in November 2016, six months after a prescribed burn of the two left-hand side sections (waste rock/laterite mixed sections where weeds occurred at high density)

4.2 Vegetation performance

Results of routine monitoring of the revegetation from 2010 to 2018 (Daws & Gellert 2011; ERA unpublished data; Gellert 2012, 2013, 2014; Gellert & Lu 2015) supports the findings from previous revegetation studies undertaken on waste rock dumps and has recorded consistent findings including the following:

- Weed density is significantly higher in the waste rock/laterite mix areas.
- Survival of tubestock is higher on the waste rock only than on the waste rock/laterite mix areas (Figure 5).
- Germination and survival of direct seeding is higher on the waste rock substrate than on the waste rock/laterite areas, but overall results are not satisfactory for a viable revegetation (without infill planting).
- Growth of tubestock is satisfactory and does not vary significantly by substrate (Figures 5 and 6).
- Majority of the tubestock plants have flowered and fruited by age 7 and dozens of the species recruited young seedlings by their own seeds (Figure 6).

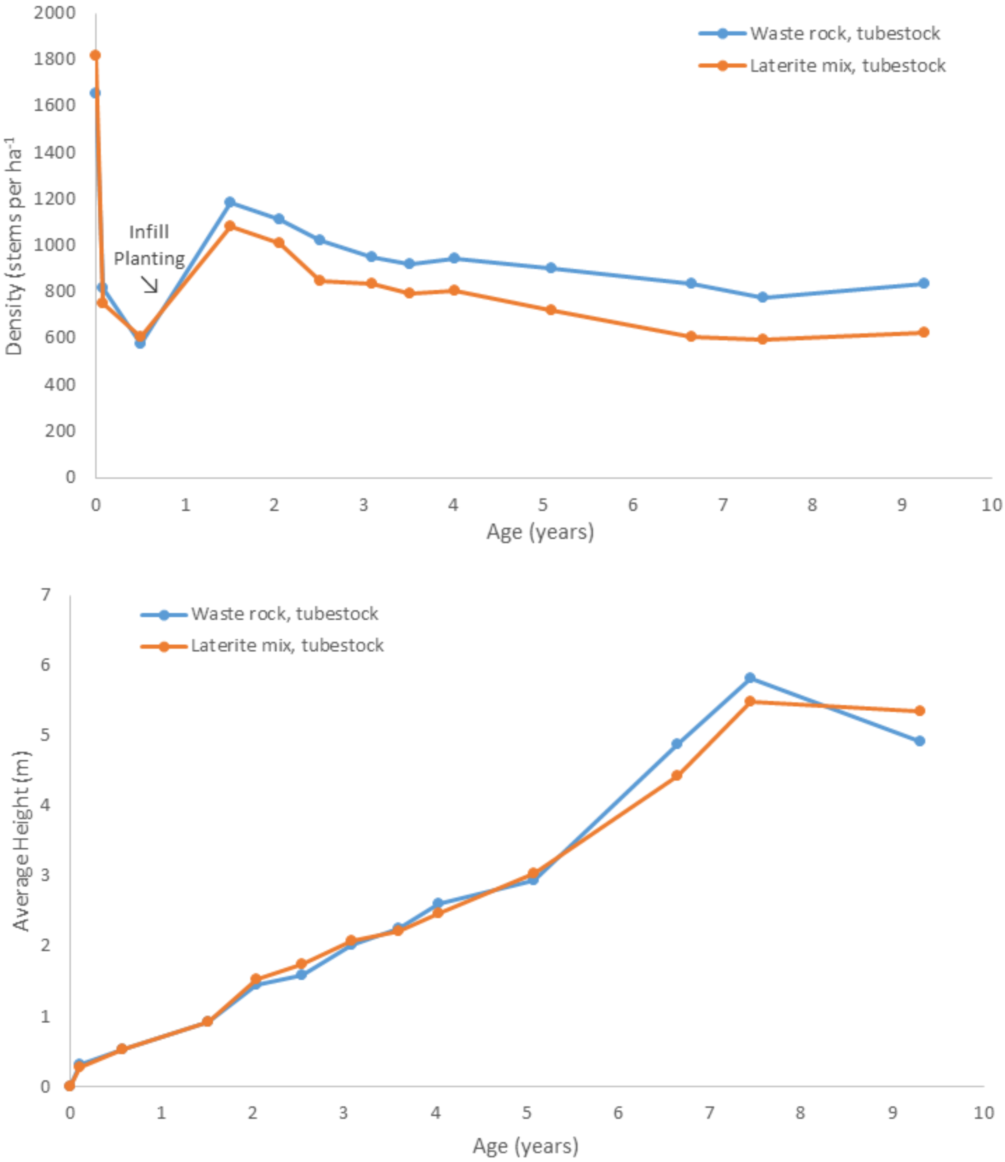

Figure 5 Density and plant growth of tubestock plants on the trial landform to June 2018

Figure 6 Seven-year-old vegetation on the waste rock only substrate of the trial landform, planted with tubestock and not irrigated

In May 2009, the TLF was surveyed for weeds. In the waste rock/laterite mix section of the TLF the average weed density was 7,083 +/- 1,828 weeds per hectare; however, no weeds were identified in the waste rock only areas (Daws & Poole 2010). They concluded that a substantial weed seed bank was introduced with the laterite material used in constructing the landform and also that the waste rock only substrate was quite hostile to self-colonisation by weed species and, presumably, non-weed species.

In October 2015, the stem density in the tubestock areas was 817 stems per hectare in the waste rock section and 613 stems per hectare in the waste rock/laterite mix areas. With natural recruits included, the density was 1,262 stems per hectare in the waste rock section, while the density was 671 stems per hectare in the waste rock/laterite mix areas. There were more natural recruits in the waste rock section (444 stems per hectare) than in waste rock/laterite mix areas (58 stems per hectare), primarily due to the absence of weeds in the waste rock section. In 2014, the self-recruiting rate in the tubestock areas of the waste rock section was 20 times higher than in the waste rock/laterite mix areas, presumably because high weed coverage in the latter prevents recruitment.

Learnings and experience from the trial landform revegetation and monitoring, as well as the change of the landform construction design, enabled ERA to refine its revegetation strategy. A key aspect of the strategy is that the growth medium layer will be predominately waste rock with no mixed laterite incorporated as previously proposed. This is due to a lack of laterite material and the higher risk of weed infestation, as demonstrated on the TLF.

5 Conclusion

The Ranger revegetation strategy was developed based on a good understanding of the natural ecological processes governing the eucalypt-dominated ecosystems of the region and also the bio-physical and hydrological condition of the final landform's growth substrate. The key strategy is to ensure the initial establishment of framework species followed by introduction of species that are either too high risk or, alternatively, too sensitive to introduce at the earlier (initial) stage. The Ranger revegetation strategy has been successfully tested at the Ranger trial landform and learnings from the trial have been incorporated into the updated revegetation strategy presented in this paper.

Well-intended aspirations to introduce all target species of all strata at the initial revegetation establishment stage should defer to an appreciation of ecological processes that will increase the likelihood that revegetation effort will result in success. Ongoing planning, research, monitoring and adaptive management should ensure the best possible revegetation outcome at Ranger mine.

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