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Development and implementation of a state and transition successional model for Ranger mine closure (Northern Territory, Australia)

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Abstract

Energy Resources of Australia Ltd (ERA) has owned and operated the Ranger uranium mine since the commencement of operations in 1980. The former Ranger mine has been one of Australia's largest uranium mines, producing in excess of 132,000 tonnes of uranium oxide over 40 years. Operations ceased in early 2021 2021 and ERA's focus is now on the rehabilitation of the Ranger Project Area. The overall goal for rehabilitation is outlined in the Environmental Requirements (ER) namely "The company must rehabilitate the Ranger Project Area to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park".

State and Transition (ST) models are non-linear conceptual models, which organise information about ecosystem change (Bestelmeyer et al. 2017). Grant (1997, 2006, 2009) proposed that ST models could be utilized to identify desired and deviated states for areas rehabilitated after mining to drive management towards an identified end state. The development of a ST model for Ranger rehabilitation commenced in 2018 and has been ongoing since. The objective of this paper is to present the latest version of the Ranger ST model and outline the next steps in its development.

The revised Ranger ST model identified the end state as a mixed savanna woodland, in line with the ERs. Seven desired states were identified along the desired trajectory at 0, 1-2, 5, 10, 15, 25+ and 50+ years. The abiotic and biotic characteristics of all states (desired and deviated) were described in detail based on existing information and expert input. Fourteen deviated states were also identified across the successional trajectory. Deviated states were characterised by significant erosion, weed or Acacia domination, high seedling mortality, lacking understorey or the overstorey being dominated by non-eucalypts. Triggers and associated actions were identified for all deviated states including remedial surface works, weed control, re-planting/seeding, prescribed burning and physical/chemical removal.

Qualitative completion criteria have been developed and signed-off by internal and external stakeholders for Ranger rehabilitation. The desired states have incorporated relevant characteristics related to these criteria. Further work is being undertaken to identify SMART (Specific, Measurable, Attributable, Realistic and Time-framed) metrics associated with the qualitative completion criteria and these will subsequently be incorporated into the ST model. An ArcGIS Project is currently being developed as the repository for monitoring data to spatially demonstrate whether rehabilitated areas are in desired or deviated states, and drive the maintenance and management programs required to meet defined completion criteria.

The development of the Ranger ST model has been a journey over the last five years. The ability to present complex successional development pathways in a simple model has assisted in obtaining alignment with the diverse range of external stakeholders with significant interests in the closure of Ranger. As rehabilitation of Ranger ramps up over the next few years, the ST model will be a critical management tool that facilitates driving rehabilitated areas along the desired successional trajectory towards the identified desired end state, through early identification of deviated states, and rapid maintenance and management intervention to ultimately drive relinquishment.

Keywords: *state and transition model, ranger, desired/deviated states, end state, maintenance, management, rehabilitation*

1 Introduction

1.1 Context

Energy Resources of Australia Ltd (ERA) has owned and operated the Ranger uranium mine since the commencement of operations in 1980. The mine is located adjacent to Jabiru, approximately 260 km southeast of Darwin in the Alligator Rivers Region of the Northern Territory. The Alligator Rivers Region has an area of approximately 28,000 km^2, encompasses Kakadu National Park, a World Heritage area listed for its cultural and natural heritage values, and parts of west Arnhem Land, all Aboriginal-owned lands. Kakadu National Park was listed under the World Heritage Convention for five of a possible 10 criteria, incorporating both cultural and natural attributes (UNESCO 2019).

The Ranger project (Ranger) area consists of 7,860 ha, with a disturbed footprint of 2,358 ha, and lies adjacent to but separate from Kakadu National Park. Ranger uranium mine (Ranger) processed its last ore in 2021 and is scheduled to complete direct closure activities between 2027 and 2028. Relinquishment of the site will be achieved once environmental requirements set out in the Australian Government's environmental protection conditions have been met (or are on a trajectory to being met). The key environmental requirements for rehabilitation of the mine site are "to establish an environment with habitats and erosion characteristics similar to adjacent areas of Kakadu National Park and stable radiological conditions that comply with national requirements and are as low as reasonably achievable" (Supervising Scientist 2018). In May 2018, Energy Resources of Australia Ltd (ERA) submitted a detailed Ranger Mine Closure Plan to the Northern Territory and Commonwealth governments for approval (Energy Resources Australia 2018). The Supervising Scientist assessed the closure criteria detailed in the RMCP and provided recommendations (based on a set of rehabilitation standards) where further evidence is required, including a framework to address Key Knowledge Needs (KKNs) (Supervising Scientist 2018). The ecosystem closure criteria were agreed on Between ERA, SSB and NLC in August 2022. An updated Ranger closure plan was published in the second half of 2022.

State and transition (ST) models are non-linear conceptual models (that can include quantitative information), which organise information about ecosystem change (Bestelmeyer et al. 2017). Grant (1997, 2006, 2009) proposed that ST models could be utilized to identify desired and deviated states for areas rehabilitated after mining to drive management towards an identified end state. A ST model describing desirable and undesirable states along possible rehabilitation trajectories at Ranger mine was developed by participants at a workshop in April 2019 (Richards et al. 2020). The development of a ST model that articulates possible rehabilitation trajectories should lead to better predictions of when rehabilitated sites will move to sustainable ecosystems that no longer require additional maintenance or management intervention, including articulation of points along the desired trajectory that represent milestones linked to completion criteria. The development of a ST model for Ranger rehabilitation has been ongoing since the original model was released in 2020. This further development is summarised in this paper.

1.2 Project objectives

The major objective was to provide a refined version of the Ranger ST model that can be operationalised in the near term to facilitate driving rehabilitated areas along the desired trajectory towards the end state, while maintaining and managing sites that have deviated. The specific objectives were to:

- Simplify and summarise the overall ST model to provide structure to the identification of desired and deviated states;

- Develop a process flow that puts the ST model in the context of other aspects of the Ranger closure project;
- Provide high level descriptions of all desired and deviated states, supported by a consistently structured detailed database that summarises the development of the model over time;
- Incorporate feedback from the expert panel engaged to review the updated biotic and abiotic characteristics of the desired and deviated states; and
- Identify the next steps to operationalize the ST model in a GIS platform and commence incorporation of monitoring data and assessments against completion criteria to drive maintenance programs.

2 Methodology

Unearthed Environmental Services (UES) were engaged by Energy Resources Australia (ERA) to critically review and undertake a revision of the existing ST Model and Adaptive Management Plan formulated by previous practitioners (ERA 2021). In late 2021, UES provided ERA a summary of the initial observations and outlined a recommended pathway to proceed with the work. The subsequent process is briefly outlined below.

2.1 Original ST model

A number of workshops were held in 2019 and 2020, facilitated by CSIRO (Commonwealth Scientific and Industrial Research Organisation), to assist in the development of the initial model (Richards et al. 2020). The workshops were attended by more than 40 people from diverse disciplines and organisations. The initial model was then further refined by ERA internally, with the development of Adaptive Management and Trigger Action Response Plan (TARPs). TARPs define the minimum set of actions required by operational staff in response to a deviation from normal environment conditions. They can be used to demonstrate the relationship between conditions. UES shared a range of initial observations in relation to the existing ST Model.

The most important initial observation related to simplification of the model to allow it to meet its primary use of early identification of deviated states and subsequent immediate maintenance implementation to drive rehabilitated areas towards the desired end state. The original model had identified five potential end states under three different climate scenarios leading to 15 possible outcomes that needed to be more targeted. The existing model was also overly focussed on intermediate age desired and deviated states, that do not currently exist nor will exist for an extended period of time. The focus needed to be on the early establishment phase (0-5 years). The definition of the desired and deviated states characteristics also needed to be standardised, with gaps identified and filled through existing data or further monitoring. It was also suggested that the TARPS should only have two levels (desired and deviated states) in place of three. While qualitative completion criteria were being finalised at the time, SMART (Specific, Measurable, Attributable, Realistic and Time-framed) metrics needed to be developed.

2.2 Site visit and identification of further existing data

A site visit and discussions with various practitioners (referenced in the Acknowledgement section) was undertaken in August 2022. UES visited various locations at Ranger including Pit 1 (18-month-old rehabilitation), the Trial Landform Area (13-year-old rehabilitation) and analogue sites, to increase familiarity with existing desired and deviated states. Interviews were held with 19 subject matter experts from five organisations (SSB - Supervising Scientist Branch, NLC - Northern Land Council, KNPS - Kakadu Native Plants Pty Ltd, ARRTC – Alligator Rivers Region Technical Committee and ERA) to identify quantitative data sources in research papers, reports and sets of data that could be used to define characteristics of desired and deviated states. Hundreds of reports and papers were identified and were reviewed and interpreted for use in the refined model. This updated draft model was presented to ARRTC in November 2022.

2.3 Expert panel feedback

A workshop was conducted in December 2022 to obtain Subject Matter Expert feedback on the abiotic and biotic characteristics of the refined desired and deviated states and identify the next steps to operationalise the ST model. Post the workshop, a site visit was undertaken to Pine Creek and Woodcutters mines as existing examples of closed and rehabilitated mines in the region, with similar desired end states. Feedback from the expert panel (over 130 individual comments) was incorporated into the detailed descriptions of states and individual responses were provided to all stakeholders who provided comments. A second draft report was released after the Expert Panel Workshop and a further meeting held in April 2023 to discuss the remaining 15 comments that needed to be addressed. Final actions were identified where appropriate and incorporated into the Final version of the ST Model.

2.4 Key messages related to the ST model for internal and external stakeholders

Ranger closure involves one of the most complex internal and external stakeholder environments of any mine in the world. It is therefore critical that the purpose of the Ranger ST model is clearly articulated to stakeholders, focussed on what the model can achieve operationally and what is outside its operating boundaries. Key messages were developed and circulated to stakeholders including:

- The purpose of the Ranger ST Model is to provide a management support tool that facilitates driving rehabilitated areas along the desired successional trajectory towards the identified desired end state.
- The ST Model provides a structure to identify rehabilitated areas that are not on the desired trajectory through monitoring and subsequent identification of appropriate maintenance/management interventions.
- The focus of the model is on identifying early deviated states (through monitoring) and early maintenance intervention to bring the areas back to a desired state in the most cost-effective way.
- The ST Model needs to be user friendly and cannot include all information that has been collected on Ranger rehabilitation over the past 50 years. This information supported the development of the model and remain as contextual information under the broad umbrella of the model.
- One Model that incorporates all abiotic and biotic features has been developed as a holistic management tool that is supported by more detailed flora and fauna work.
- The Model focusses on waste rock rehabilitation, but further models can be developed for the Land Application Areas and other disturbed sites within the Ranger lease area if required.

3 Results and discussion

3.1 Refined Ranger ST model

A process flow diagram focused on inputs and process flows was developed to put the Ranger ST model into context of other previous and ongoing elements (Figure 1). Input to the model included data/reports, the legislated ERs, qualitative completion criteria, TARPs and Expert Opinion. Some of these input pathways are multi-directional, such as completion criteria that will be refined in light of the developed ST model. The model itself will be housed in a GIS platform that will receive monitoring data from rehabilitated areas and identify areas requiring maintenance that do not meet identified completion criteria. The model will be iteratively updated over time as it is utilised and improved. Ultimately, rehabilitated areas that meet all completion criteria will be identified for early relinquishment and ultimately when all areas meet all completion criteria, potential incorporation into Kakadu National Park.

The revised Ranger ST model identified the end state as a mixed savanna woodland. Seven desired states were identified along the desired trajectory at 0, 1-2, 5, 10, 15, 25+ and 50+ years (Figure 2). The abiotic and biotic characteristics of all states (desired and deviated) were described in detail based on existing information and expert input. Fourteen deviated states were also identified across the successional trajectory. Deviated states were characterised by significant erosion, weed or *Acacia* domination, high seedling mortality, lacking understorey or the overstorey being dominated by non-eucalypts. Triggers and associated actions were identified for all deviated states including remedial surface works, weed control, re-planting/seeding, prescribed burning and physical/chemical removal.

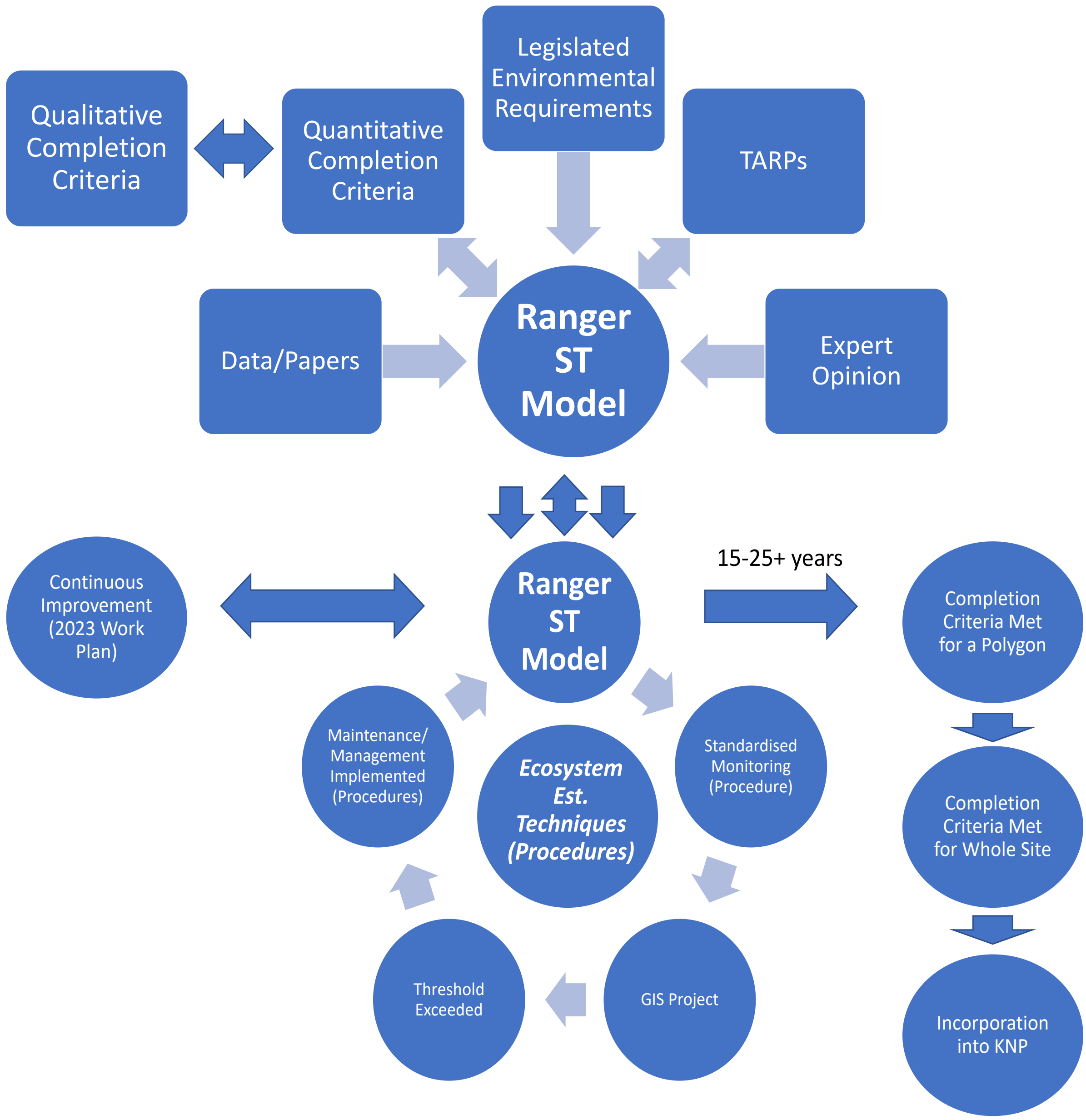
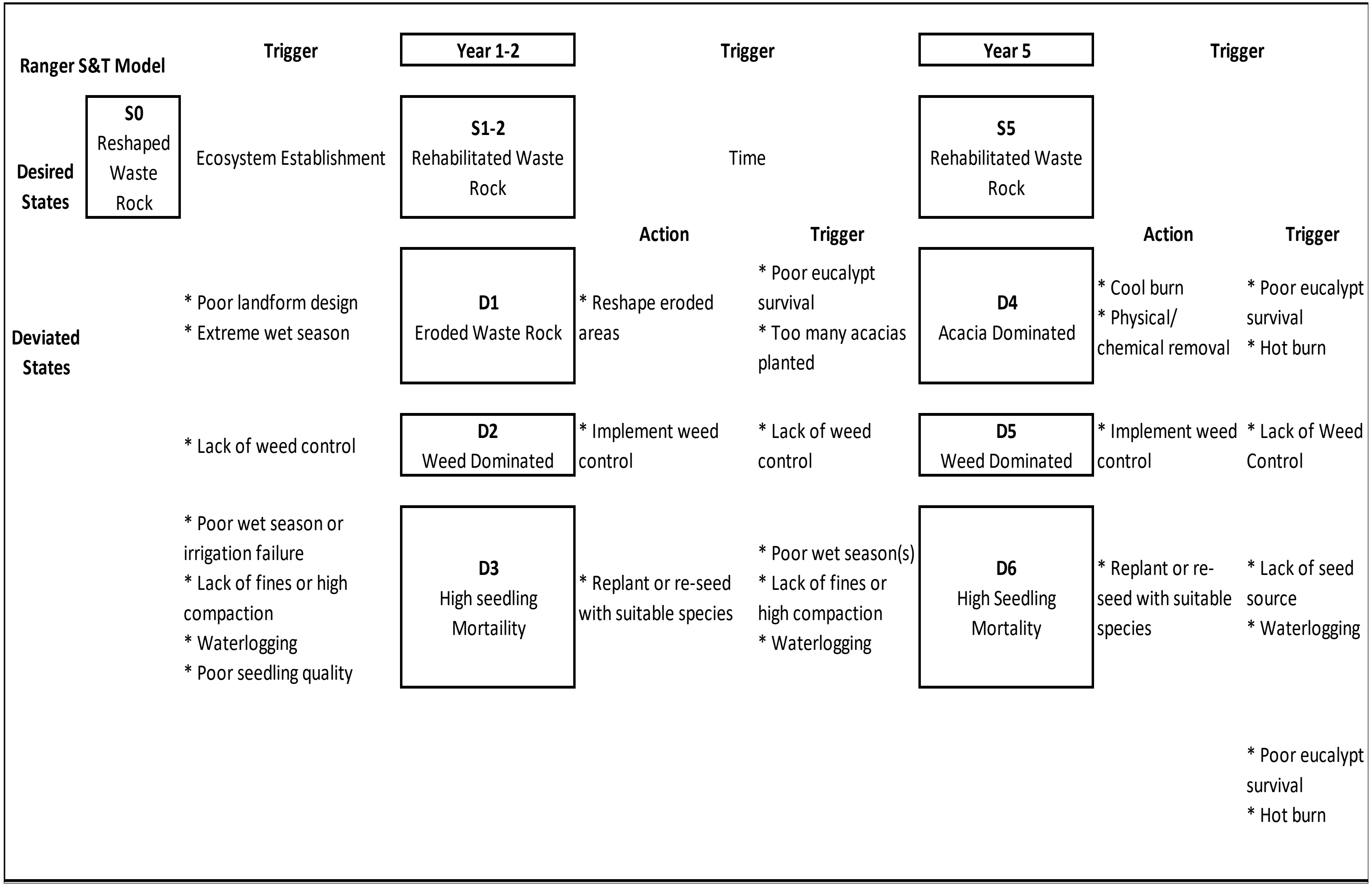


Figure 1: Summary of inputs and process flows for the Ranger ST model iterative development


Ranger S&T Model
Trigger
Year 1-2
Trigger
Year 5
Trigger
Desired States
S0
Reshaped Waste Rock
Ecosystem Establishment
S1-2
Rehabilitated Waste Rock
Time
S5
Rehabilitated Waste Rock
Action
Trigger
Action
Trigger
Deviated States
* Poor landform design
* Extreme wet season
D1
Eroded Waste Rock
* Reshape eroded areas
* Poor eucalypt survival
* Too many acacias planted
D4
Acacia Dominated
* Cool burn
* Physical/ chemical removal
* Poor eucalypt survival
* Hot burn
* Lack of weed control
D2
Weed Dominated
* Implement weed control
* Lack of weed control
D5
Weed Dominated
* Implement weed control
* Lack of Weed Control
* Poor wet season or irrigation failure
* Lack of fines or high compaction
* Waterlogging
* Poor seedling quality
D3
High seedling Mortaility
* Replant or re-seed with suitable species
* Poor wet season(s)
* Lack of fines or high compaction
* Waterlogging
D6
High Seedling Mortality
* Replant or re-seed with suitable species
* Lack of seed source
* Waterlogging
* Poor eucalypt survival
* Hot burn

Year 10	**Trigger**		**Year 15**	**Trigger**		**Year 25+**	**Trigger**	**Year 50+**
S10 Rehabilitated Waste Rock	First Burn		**S15** Rehabilitated Waste Rock	Second Burn		**S25+ (End State)** Rehabiltiated Waste Rock	Mosaic Burning	**Sx (End State)** Mixed Savanna Woodland
	Action	**Trigger**		**Action**	**Trigger**		**Trigger**	
D7 Acacia Dominated	* Cool burn * Physical/ chemical removal	* Poor eucalypt survival * Hot burn	**D11** Acacia Dominated	* Cool burn * Physical/ chemical removal	Time		Time	
D8 Weed Dominated	* Implement weed control	* Lack of Weed Control	**D12** Weed Dominated	* Implement weed control	Time		Time	
D9 No Understorey	* Replant or re-seed with suitable species	* Lack of seed source	**D13** Lacking Understorey	* Replant or re-seed with suitable species	Time		Time	
D10 Non-Eucalypt Overstorey	* Thinning of overstorey * Replanting eucalypts	* Poor eucalypt survival * Hot burn	**D14** Non-Eucalypt Overstorey	* Thinning of overstorey * Replanting eucalypts	Time		Time	

Figure 2a-b: Diagram summarizing the refined Ranger ST model (Figure should be read as if it was left to right)

3.2 Characteristics of desired states

The abiotic and biotic characteristics of the desired states for six rehabilitation ages (0, 1-2, 5, 10, 15 & 25+ years-old) and a single desired end state were concisely summarised from the refined raw data (Table 1). The abiotic identifiers are those relating to growth media, nutrients and water, while the biotic features relate to flora, fauna and fungi/bacteria). Key abiotic features that develop over time in the desired states are a stable landform, litter decomposition, nutrient cycling and horizons in the soil profile. Key biotic features relate to over and mid-storey density, lack of weed species, understorey richness, development of vegetation structure, manageable fuel load development and recolonisation by invertebrate and vertebrate fauna groups. An example of the full abiotic and biotic characteristics description is provided for the 15-year-old desired state (Table 2). This level of detail exists for all seven identified desired states.

Table 1: Key abiotic and biotic characteristics of the seven identified desired states

Desired State	Abiotic	Biotic
S0	* Waste rock with suitable proportion of fines * Growth medium scarified/ripped and free draining * Erosion management in place * Available nutrients low except near planted seedlings	* ~1000 stems/ha of overstorey and midstorey species, weeds <5% * No organic matter and microbial activity, very low fuel load * Scattered invertebrate fauna * Select vertebrate fauna present (e.g. lizards)
S1-2	* No or limited erosion, waste rock weathering * Available nutrients low except near planted seedlings * Nitrogen fixing spp. Established	* Overstorey/midstorey species density at >650 stems/ha * Understorey cover low (5-20%); Weed cover <5% * Scattered microbial/fungal activity, fuel load very low to low * Select invertebrate groups present (e.g. ants, grasshoppers) * Some tolerant vertebrate species present (e.g. rock rats, bandicoots)
S5	* Stable landform present * Increasing fines at surface * Soil nitrogen increasing, nutrient cycling has commenced	* Overstorey/Midstorey species density at 400-600 stems/ha (3-5 m) (>10 spp./ha) * Understorey cover increasing (20-50%); Weed cover <10% * Stratification of vegetation has commenced * Microbes/fungi active, litter cover developing (>30%) * Invertebrates, reptiles, birds and small mammals present
S10	* Stable landform present * Litter decomposition and nutrient cycling occurring * No signs of nutrient deficiencies	* Overstorey/Midstorey species density at 300-500 stems/ha (5-10 m, 5-10 cm diameter)(>10 spp./ha) * Understorey richness increasing (>30/ha); Weed cover <10% * Stratification of vegetation clear with heterogeneity increasing * Soil microbial/fungal activity high; Fuel load moderate to high * Flowering and seedling recruitment occurring * Invertebrates, reptiles, birds and small mammals present with moderate richness

Desired State	Abiotic	Biotic
S15	* Stable landform present * A1 horizon starting to form * Litter decomposition and nutrient cycling occurring * Moderate C:N ratio	* Overstorey/Midstorey species density at 150-500 stems/ha (10-15 m, 10-20 cm diameter) (>10 spp./ha) * Understorey cover moderate (20-50%); Richness high (>30/ha) Weed cover <10% * Three strata clearly visible * Soil microbial/fungal activity high; Fuel load moderate susceptible to fire * Flowering and seedling recruitment occurring * Invertebrates, reptiles, birds and small mammals present with high richness
S25+	* Stable landform present * A1 horizon present with clay loam subsoil developing * Litter decomposition and nutrient cycling occurring * High C:N ratio	* Overstorey/Midstorey species density at 150-400 stems/ha (15-25 m, 20-40 cm diameter)(>10spp./ha) * Understorey cover moderate (30-60%); Richness high (>40/ha) Weed cover <10% * Three strata obvious, heterogeneity high * Soil microbial/fungal activity high; Fuel load moderate susceptible to fire * Flowering and seedling recruitment regularly occurring * Invertebrates, reptiles, birds and small mammals present with high richness * Fauna utilising habitat and breeding
Sx (End State)	* Stable landform present * A1 and B horizons present * Nutrient cycling in equilibrium * Moderate C:N ratio	* Overstorey/Midstorey species density at 150-400 stems/ha, with eucalypts dominant (15-25 m, 20-50 cm) (>10spp.ha) * Understorey cover moderate (30-60%); Richness high (>45/ha) Weed cover <10% * Three strata obvious, heterogeneity high * Soil microbial/fungal activity high; Fuel load moderate susceptible to fire * Flowering and seedling recruitment occurring in all species * Invertebrates, reptiles, birds and small mammals present with high richness * Fauna utilising habitat and breeding, including hollow-dependent species

S15 Rehabilitation
ABIOTIC and NUTRIENT CYCLING: *Physical: Stable landform present, A1 horizon starting to form. *Chemical: Litter decomposition and nutrient cycling occurring, moderate C:N ratio, Leaf litter cover high (30-60% - not immediately after fire). **BIOTIC: Native Vegetation** *Structure: Three strata clearly present (overstorey, midstorey, understorey), heterogeneity moderate. Overstorey (and Midstorey) composition, species richness, total abundance, size class distribution and canopy cover are statistically similar to, or on trajectory towards, the reference ecosystem): *Composition: Overstorey/Midstorey 150-500 stems/ha (10-15 m, 10-20 cm diameter), eucalypts dominant in the overstorey (>10ssp./ha); most species are flowering and fruiting with increased recruitment. *Understorey: composition, species richness, total abundance, size class distribution and canopy cover are statistically similar to, or on trajectory towards , the reference ecosystem: 20-50% ground cover including all functional groups, richness >30 species/ha, localised features (e.g. rockpiles, depressions, cultural species) integrated into the landscape. *Function: Microbes/fungi present with high richness. **BIOTIC: Native Fauna** *Invertebrate: Diversity of classes and species is high and on trajectory towards the reference ecosystem. *Vertebrate: Most common non hollow-dependent species (reptiles, birds, ground-based mammals) utilising habitat including breeding. **BIOTIC: Threats** *Introduced Flora has <10% cover with no transformer weeds present. *Some exotic fauna present (cats, pigs & buffalo) but at abundances where control requirements are no greater than KNP. **BIOTIC: Resilience** *Fire: Fuel Load: Moderate; Resilience: Susceptible to fire every year, continued careful introduction of cool burns in mosaic patterns to some areas. -Ecosystem showing resilience to natural disturbance: e.g. suckering/resprouting after damage or top-death, some saping and healing after insect damage etc.

Table 2. The abiotic and biotic characteristics of the 15 year-old desired state

3.3 Characteristics of deviated states

The abiotic and biotic characteristics of the identified deviates states were concisely summarised from the refined raw data (Table 3). Some deviated states are defined across time categories (e.g. 5, 10 and 15 years-old), while for others it is assumed that early intervention will occur and be successful (e.g. eroded waste rock). The most appropriate management options include reshape eroded areas, replant or reseed as required and manage weeds. Further work is required to develop detailed procedures relating to the management options to move rehabilitation areas that are in deviated states back to the desired successional trajectory. An example of the full abiotic and biotic characteristics description is provided for the 15-year-old *Acacia* dominated deviated state (Table 4). This level of detail exists for all 14 identified deviated states. It was decided that the characteristic descriptions for deviated states would only focus on those that were different from the desired states to reduce detail.

Table 3: Key abiotic and biotic characteristics of the grouped 14 identified deviated states, and proposed management actions

Deviated State	Descriptor	Time Categories	Abiotic/Biotic	Management
D1	Eroded Waste Rock	1-2	* Erosion visible * Landform unstable * Little or no vegetation present	* Reshape eroded areas * Replant or reseed as required * Manage weeds
D2, D5, D8 & D12	Weed Infestation	1-2 5 10 15	* Weed cover >10% * Feral animals present * Overstorey lacking * Fuel load increasing over time * Regular fires of high intensity	* Control weeds with physical, chemical or biological controls * Replant or re-seed as required * Implement feral animal control program
D3 & D6	High Seedling/ Plant Mortality	1-2 5	* High levels of mortality in overstorey and midstorey (<650 stem/ha decreasing over time) * Low native plant cover; Moderate weed cover * Signs of stress in remaining vegetation * Faunal activity reduced * High litter cover (>75%) with low C:N ratio	* Replant or reseed as required * Manage weeds
D4, D7 & D11	Acacia Dominance	5 10 15	* 500-1000 stems/ha Acacias (>70% cover) * Low understorey cover (<5%) * High fuel loads; prone to high intensity fires * High recruitment of Acacias following hot burn * Faunal activity high with increased abundance of suited species	* Utilise physical or chemical means to remove the excess plants (Acacias) * Undertake a low intensity early dry or early wet season burn * Replant or reseed as required
D9 & D13	Lacking Understorey	10 15	* Overstorey and mid-storey density and cover similar to desired state * Understorey density and cover low * Faunal activity reduced	* Replant or reseed as required * Manage weeds
D10 & D14	Non-Eucalypt Overstorey	10 15	* Lack of eucalypts in the overstorey * Increased density of mid-storey species (600 stems/ha) * Understorey density and cover low * Faunal activity reduced	* Utilise physical or chemical means to remove the excess plants (Kapoks) * Undertake a low intensity early dry or early wet season burn * Replant or reseed as required

D11 Acacia Dominance
ABIOTIC and NUTRIENT CYCLING: *Chemical: Increased soil nitrogen due to elevated Acacia density, low C/N ratio. **BIOTIC: Native Vegetation** *Composition: Overstorey: Increased Acacia stem density (>400 stems/ha, >50% cover) with active recruitment, potentially reduced density of other woody species; Understorey: Further reduced grass cover due to shading out. *Structure: Stratification influenced by Acacia dominance, shrubby midstorey or Acacia dominated overstorey. *Function: Increased litter cover; Developing seed bank of Acacia spp. which will rapidly regenerate following fire or clearing. **BIOTIC: Native Fauna** *Invertebrate Colonisation: Greater abundance of species associated with Acacia spp. and high soil nitrogen levels.*Vertebrate Colonisation: Decreased faunal diversity, favouring some smaller birds (e.g. bar-shouldered doves, partridge pigeons). **BIOTIC: Threats** *Increased presence of exotic species (pigs). **BIOTIC: Resilience** *Fire: Fuel load: Moderate to high, increased due to litter cover and dominance of flammable Acacia's; Resilience: Susceptible to fire with risk of increased intensity impacting non-Acacia spp. and further increased dominance of Acacias following regeneration.

Table 4. Example of deviated state characteristics of 15 year rehabilitation

4 Further development of the Ranger ST model

The next steps for the Ranger ST model iterative development will include:

1. Development of Completion Criteria Metrics.

The qualitative completion criteria have been approved for use and with the addition of the ST model data and monitoring of analogue sites, the quantitative completion criteria metrics can now be developed. Once these are developed and endorsed, they can be incorporated into the desired states characteristics and the associated GIS interface.

2. Development of Complimentary Monitoring Program.

A number of monitoring programs exist at Ranger already and it is important that these are reviewed and aligned with the requirements of the ST model and the quantitative completion criteria metrics. Some additional monitoring may be required, but equally some existing monitoring may no longer be relevant and required in the closure phase.

3. GIS Interface.

A GIS interface is currently being developed that will house the SMART metrics of the state and transition model. It is planned that each rehabilitation polygon will contain important ecosystem establishment technique information, in addition to attributes relating to completion criteria metrics for each desired state time category and maintenance/management activities that are planned or completed. The completion criteria attributes will include for example: species richness (number), canopy cover (% cover), Soil Nutrients (Carbon/Nitrogen Ratio), Midstorey stems/ha (density) and weed cover (% cover), to name a few. This can then identify which areas on the site require further maintenance/management interventions to ensure that all rehabilitation polygons are on a trajectory towards the end state ensuring the completion criteria will be met to a stable, self-sustaining ecosystem.

4. Ecosystem Establishment and Maintenance/Management Procedures.

ERA will continue to fine tune ecosystem establishment procedures developed over the last decade and refine maintenance and management practices that are required to drive rehabilitated areas towards the identified completion criteria metrics. These procedures are required to ensure consistent implementation of activities and to allow for continual improvements to ecosystem establishment prescriptions and maintenance/management techniques.

5. Implementation of the GIS Spatial Interface.

Standardised monitoring will occur against the completion criteria metrics and be entered into the GIS system to facilitate spatial investigation tracking rehabilitated areas on the desired trajectory and those requiring further maintenance/management activities. The implementation of the interface tool and its use daily will assist in the overall day to day management of rehabilitate areas and facilitate achievement of the potential goal of integration into Kakadu National Park.

5 Conclusion

The Ranger State and Transition Model demonstrates the significant potential of this process to be applied to mining rehabilitation to drive areas towards an identified end-state to facilitate achievement of completion criteria and subsequent lease relinquishment. The Model needs to be seen as a management tool that assists to rapidly identify rehabilitated areas that are not meeting defined completion criteria and quickly implement maintenance activities to return them to the desired successional trajectory. This has significant potential to be applied at a range of mines around the globe. While in its closure phase, ERA have refined and developed a model to identify key SMART metrics to establish quality rehabilitation that can be managed through a GIS platform on a day-to-day basis. The state and transition model will be updated regularly as new monitoring information becomes available in relation to the desired state of the rehabilitation and any additional deviated states that may be observed in the future. Importantly, during the development process of the ST model, the engagement of a diverse range of stakeholders assisted in keeping alignment and momentum.

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References

Bestelmeyer BT., Ash A, Brown JR, Densambuu B, Fernández-Giménez M, Johanson J, Levi M, Lopez D, Peinetti R, Rumpff L & Shaver P, 2017, State and Transition Models: Theory, Applications, and Challenges. In: *Rangeland Systems: Processes, Management and Challenges* (ed D. D. Briske) pp. 303-45. Springer International Publishing, Cham.

Energy Resources Australia 2018, *Ranger mine closure plan*. http://www.energyres.com.au/sustainability/closureplan/

Energy Resources of Australia Ltd 2020, *Ranger Mine Closure Plan, issued October 2020*, Revision number 0.20.0, Energy Resources of Australia Ltd.

Energy Resources of Australia Ltd 2021, *Ranger State-and-Transition Model & Adaptive Management Framework*. Energy Resources of Australia Ltd.

ERA, SSB & NLC 2021, *Generic Completion Criteria for ERA mine.*

Grant, CD 1997, Fire Ecology in Rehabilitated Bauxite Mines in the Jarrah (Eucalyptus marginata) Forest of South-western Australia. PhD Thesis, The University of Western Australia.

Grant, CD 2006. State-and-transition successional model for bauxite mining rehabilitation in the jarrah forest of Western Australia. *Restoration Ecology* 14: 28-37.

Grant, CD 2009, State-and-Transition Models for Mining Restoration in Australia. In: Hobbs, R. J and K. N. Suding (eds) '*New Models for Ecosystem Dynamics and Restoration*'. Pages 280-294. Island Press, Washington, USA.

Richards, AE, Bartolo, R, Loewensteiner, D, Meek, I, Warnick, A 2020, *Rehabilitation trajectories for Ranger Mine*. CSIRO, Sydney, Australia.

Supervising Scientist 2018, *Assessment report: Ranger Mine closure plan* rev #: 0.18.0 May 2018. In: Internal Report 658 p. 110. Supervising Scientist, Darwin.

UNESCO 2019, *Kakadu National Park,* UNEWSCO World Heritage Convention, viewed 12 September 2020, https://whc.unesco.org/en/list/147