Mine Closure 2019 - AB Fourie & M Tibbett (eds)

doi:10.36487/ACG_rep/1915_100_Bartolo

An approach to an ecosystem restoration standard for Ranger Uranium Mine

RE Bartolo *Department of the Environment and Energy, Australia*

J Nicholson *Department of the Environment and Energy, Australia*

M Rudge *The University of Queensland, Australia*

D Loewensteiner *Department of the Environment and Energy, Australia*

T Whiteside *Department of the Environment and Energy, Australia*

P Erskine *The University of Queensland, Australia*

M Barnes *Department of the Environment and Energy, Australia*

CL Humphrey *Department of the Environment and Energy, Australia*

Abstract

Rehabilitation of the Ranger mine site, located in the Northern Territory, Australia, must be completed by the mine operator, Energy Resources Australia Limited (ERA), by 2026. The Supervising Scientist (Australian government's Department of the Environment and Energy) has developed a series of rehabilitation standards against which the success of rehabilitation can be measured. These standards are not mandatory but will form the basis of the Supervising Scientist's advice on ERA's proposed closure criteria and rehabilitation plans, and the eventual success of rehabilitation.

A number of the standards describe the requirements for the onsite environment, including the performance of, and restoration associated with, the re-constructed landform. This presentation will focus on the ecosystem restoration standard and is complementary to the landform stability standard (presented at this forum also). The ecosystem restoration standard considers all requirements for restoring the terrestrial ecosystem of the Ranger Project Area (including riparian areas). The paper addresses the following topics:

- *The overall objective of the standard.*
- *The application of the standard (ecosystem similarity and sustainability and ecosystem trajectory approach).*
- *Relevant requirements (environmental requirements and aspirations of Traditional Owners).*
- *Recommended attributes and measures.*
- *The scientific basis underpinning the standard (guidelines used to develop the recommended attributes and measures, and summary of scientific evidence).*
- *The future knowledge needs to be addressed to ensure appropriate management of the key risks to the environment from the rehabilitation.*
- *Current research into deriving measures and scaling these measures (traditional ground and drone surveys).*

Keywords: *closure criteria, ecosystem restoration, rehabilitation standard, scaling, drones*

1 Introduction

1.1 The mine site

Ranger Uranium Mine, operated by Energy Resources Australia Ltd is located east of Darwin, Northern Territory, Australia (Figure 1). It is surrounded by, but is not a part of, the World Heritage listed, Kakadu National Park and is located upstream of Ramsar listed floodplains and wetlands. Mining of uranium mine oxide commenced at the site in 1981, with milling of stockpiles to cease by 2021 and rehabilitation works scheduled to be completed by 2026.

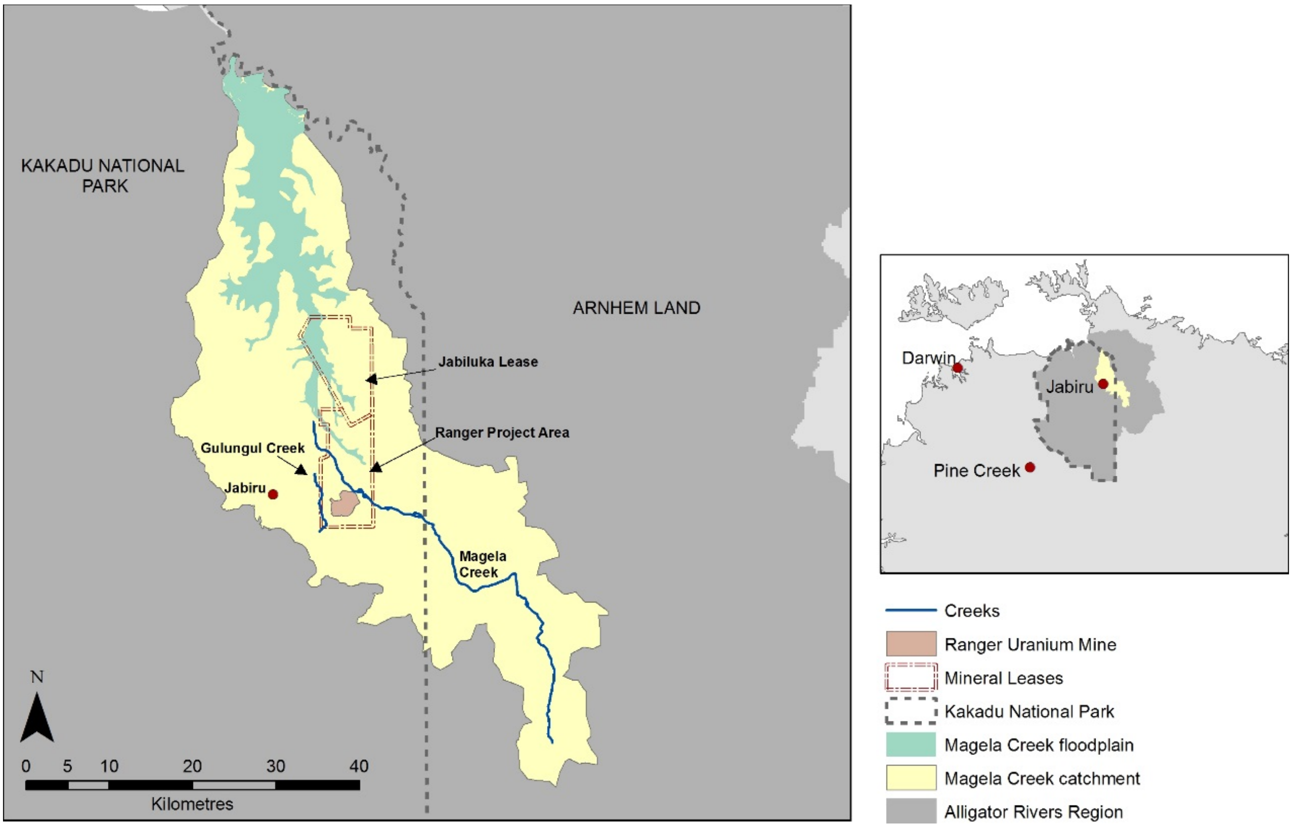

Figure 1 Location of Ranger Uranium Mine

1.2 Environmental requirements and objectives for rehabilitation

Due to the ecologically and culturally sensitive setting of Ranger mine site, the Australian Government specified the environmental protection conditions with which the mine operator must comply in the *Environmental Requirements of the Commonwealth of Australia for the operation of the Ranger Uranium Mine* (Environmental Requirements) (Department of the Environment and Heritage 1999). The main objective in the Environmental Requirements relating to ecosystem restoration is:

> *"…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."*

The Department of the Environment and Energy's Supervising Scientist Branch is developing a series of rehabilitation standards (Supervising Scientist 2018a) to measure the rehabilitation outcomes for Ranger mine site in the context of site closure. These standards are based on the objectives specified in the Environmental Requirements and the best available science, and cover the following six themes: radiation, water and sediment, ecosystem restoration, soils, landform and culture. Each of the rehabilitation standards for Ranger Uranium Mine has been developed in accordance with section 5c of the *Environment Protection (Alligator Rivers Region) Act 1978* (Commonwealth of Australia 1978) and is advisory only.

The aspirations of the Mirrar Traditional Owners have been acknowledged in the development of the ecosystem restoration rehabilitation standard. These aspirations support the use of a reference ecosystem approach to derive rehabilitation targets and a desire to return the site to a similar state to that which existed before mining. As stated in Garde (2015), the Mirrar Traditional Owners desire that the restored ecosystem on the Ranger Project Area: include 59 specific plant species, some of which are native bush foods; reflect stable patterns of local native vegetation, including the rehabilitation of riparian corridors; and be managed using a regime that reinstates traditional Mirrar fire management and the eradication of all weeds onsite.

2 Application of the standard

The achievement of long-term sustainability of the restored ecosystem on the rehabilitated site and its degree of similarity to the surrounding areas will be assessed by comparison to a reference ecosystem. The standard (Supervising Scientist 2018b) defines the sustainability and similarity goals that must be achieved to demonstrate the success of ecosystem restoration. The numerical values for the indicators that will quantify these goals are under development and will be included in the standard once available.

Full ecosystem restoration of the Ranger mine site will take many decades. To account for this, restoration success can be assessed against modelled restoration trajectories. The trajectories represent multiple possible restoration outcomes based on factors that may influence the progress of restoration over time, such as fire, weeds, climate, and edaphic properties. Ongoing monitoring will be required to: assess where the ecosystem has developed relative to the possible trajectories over time; inform management activities; and validate and assess confidence in the model. The trajectory model can then be used to determine the point at which the ecosystem is likely to progress to successful restoration without further management input.

It should be noted that this standard is complementary to the landform stability standard (Supervising Scientist 2018c).

3 Guidelines and standards used to develop closure metrics

The ecosystem restoration standard has been developed using the approach described in the National Restoration Standards (Society for Ecological Restoration 2016) developed by the Society for Ecological Restoration Australia. The definition of 'ecological restoration' in the National Restoration Standards aligns well with the rehabilitation objectives for the Ranger Uranium Mine, requiring long-term sustainability of the restored ecosystem and its similarity to the surrounding areas.

The National Restoration Standards recommend the use of ecosystem attributes to measure rehabilitation success according to similarity and sustainability. Those attributes that relate to the requirement for similarity are species composition and community structure, and those that relate to the requirement for sustainability are the absence of threats, ecosystem functionality, external exchanges and physical conditions. Sub-attributes are those aspects of the attributes that are measured to assess the achievement of the goals. A list of the attributes, sub-attributes and their associated goals, are listed in Tables 1 (ecosystem similarity) and 2 (ecosystem sustainability).

Most of the similarity and sustainability goals in Tables 1 and 2 were based on recommendations in the Western Australian guidance statement, *Rehabilitation of terrestrial ecosystems* (Environmental Protection Authority 2006), and the Queensland government guideline, *Rehabilitation requirements for mining resource activities* (Department of Environment and Heritage Protection 2014).

The standard follows the approach for ecological restoration detailed in the National Restoration Standards. The fundamental aspects of this approach include:

1. Defining an appropriate reference ecosystem that can be used to set similarity and sustainability goals for restoration.
2. Measuring key indicators that enable comparison between the restored site and the reference ecosystem over time to assess the success of ecosystem restoration.

The National Restoration Standards define a reference ecosystem as a model adopted to identify the particular ecosystem that is the target of the restoration project. The reference ecosystem used here will be defined using data from the area surrounding the Ranger Uranium Mine to ensure that it is representative. The success of ecosystem restoration can be assessed by determining if the attributes of the rehabilitated site are the same, or approaching the same condition, as the reference ecosystem. The reference ecosystem is broadly based and sufficiently diverse to capture specific community types, should the edaphic properties of the restored ecosystem require these.

This assessment is based on key indicator values that are derived from the reference ecosystem based on its compositional, structural and functional ecosystem attributes, including the range of spatial and temporal variability. Numerical measures for these indicator values will be derived using population, assemblage or other measured statistics for key attributes, and presented as mean, quantiles and associated confidence values. These indicator values may be updated over time as the reference ecosystem changes, or as additional knowledge becomes available. This assessment, where feasible, will be done at a spatial scale that is similar to the disturbed area of the Ranger Project Area (approximately 1,000 ha) using remote sensing technology. Once again, it should also be noted that the reference ecosystem is broadly based and sufficiently diverse to capture specific community types, should the edaphic properties of the restored ecosystem require these.

In addition to the Queensland and Western Australian sustainability and similarity goals, other goals specific to the region were included, as recommended in the National Restoration Standards. For example, ecosystem resilience after the reintroduction of fire is a site-specific sustainability goal that acknowledges the role of fire in the tropical savannas of northern Australia. Other goals were selected based on technological advances, such as the use of environmental DNA (eDNA) analysis as a low-cost method for characterising the microbial diversity of restored soils (Williams et al. 2014).

The National Restoration Standards state that ‘where mining is undertaken in natural areas, the highest standard of ecological restoration is expected’. In addition to this, the ERs and the aspirations of the Mirrar Traditional Owners require a high standard of ecosystem restoration for the Ranger Project Area. The National Restoration Standards describe a one-to-five-star recovery scale that can be used to measure progress towards a fully restored state. To ensure the achievement of the high standard of ecosystem restoration required for the Ranger Project Area, this rehabilitation standard recommends goals that represent a five-star recovery rating.

4 Attributes and measures for ecosystem restoration

Key ecosystem attributes are presented for similarity goals (Table 1) and sustainability goals (Table 2). These attributes and measures are similar to those proposed by the mine operator (Energy Resources of Australia 2018).

Table 1 Rehabilitation standard for ecosystem similarity

Attribute	Sub-attribute	Goal
Species composition	Species composition of vegetation	Overstorey and understorey assemblages and species abundance are highly similar[a] to, or on a secure trajectory towards, those of the reference ecosystem. Stems per hectare and per cent cover of overstorey and understorey species are highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
	Species composition of fauna	Assemblages and species relative abundance of fauna (including threatened species) are highly similar to, or on a secure trajectory towards, those of the reference ecosystem.
	Species richness (number of species)	Species richness of overstorey and understorey flora and fauna is highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
Community structure	Vegetation strata	Canopy cover, understorey and ground cover are highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
	Size class distribution of trees and shrubs	Woody plant species size class distribution and total basal area are highly similar to, or on a secure trajectory towards, those of the reference ecosystem.
	Vegetation distribution ('naturalness')	Patch metrics (e.g. isolation, proximity and dispersion) are highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
	All trophic levels of fauna	Trophic guilds of fauna are highly similar to, or on a secure trajectory towards, that of the reference ecosystem.

[a] 'Highly similar to reference ecosystem' based on the terminology applied in the SERA standards for five-star recovery

Table 2 Rehabilitation standard for ecosystem sustainability (continued next page)

Attribute	Sub-attribute	Goal
Ecosystem function	Recruitment of vegetation	Rates of vegetation recruitment are highly similar to, or on a secure trajectory towards, those of the reference ecosystem. Phenology of vegetation, including productivity of flowers, seeds and fruit, is highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
	Nutrient cycling	Soil biota, measured by environmental DNA or other genomic techniques, provide evidence that nutrient cycling could indefinitely sustain the species and processes, similar to, or on a secure trajectory towards, those of the reference ecosystem. Litter decomposition rates that could indefinitely support the species and processes are similar to, or on a secure trajectory towards, those of the reference ecosystem. Abundance and diversity of key invertebrate species (e.g. ants, termites) are indicative of nutrient cycling that could indefinitely sustain the species and processes similar to, or on a secure trajectory towards, those of the reference ecosystem.

Attribute	Sub-attribute	Goal
	Faunal usage	Faunal occupation and usage of habitat are highly similar to, or on a secure trajectory towards, those of the reference ecosystem.
	Habitat availability	Occurrence and abundance of key habitat features (e.g. hollow logs, tree hollows) are highly similar to, or on a secure trajectory towards, those of the reference ecosystem.
	Resilience to fire	After the reintroduction of a fire regime similar to that in adjacent areas of Kakadu National Park, mortality and recovery rates of plants and animals are highly similar to those of the reference ecosystem.
	Resilience to extreme weather events, pests and disease	Ecosystem resilience to disturbances such as high wind and disease is highly similar to that of reference ecosystem.
External Exchanges	Habitat connectivity	Lack of physical barriers (i.e. fences, roads etc.) provides the potential for external exchanges highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
		Evidence of passive regeneration and dispersal, including dispersing fauna (pollinators/frugivores) highly similar to, or on a secure trajectory towards, that of the reference ecosystems.
		Patch metrics such as connectivity are highly similar to, or on a secure trajectory towards, that of the reference ecosystem.
Physical conditions	Plant available water	Plant available water is sufficient to sustain the species and processes similar to that of the reference ecosystem.
	Suitable growth medium	The growth medium is capable of sustaining the species and processes similar to that of the reference ecosystem.
	Nutrient availability	Plant available nutrients (especially nitrogen and phosphorus) can sustain, or are on a secure trajectory toward that which can sustain, vegetation similar to that of the reference ecosystem.
		Organic matter content can indefinitely sustain, or is on a secure trajectory toward that which can sustain, the species and processes similar to that of the reference ecosystem.
Absence of threats	Weeds	Weed composition, abundance and density are no greater than that of the reference ecosystem.
	Pests	Pest composition, abundance and density are no greater than that of the reference ecosystem.
	Fire	Fire management is comparable to, and fire impacts no greater than fire regimes in, the reference ecosystem.

5 Future knowledge needs

Rehabilitation planning can only be based on the best available information at a given time, but this should not preclude the continual improvement of the knowledge base and its subsequent application where directly relevant and possible. The Supervising Scientist, through its Key Knowledge Needs, has identified the knowledge required to ensure appropriate management of the key risks to the environment from the rehabilitation of the Ranger Uranium Mine. For ecosystem restoration, these knowledge needs (Department of the Environment and Energy 2018) are shown in Table 3.

Table 3 Key Knowledge Needs for ecosystem restoration (continued next page)

Environmental requirement link	Key Knowledge Need (KKN)	Questions
Ecosystem similarity	ESR1. Determining the characteristics of ecosystems in the areas surrounding the Ranger Project Area.	ESR1A. What are the key characteristics of the terrestrial ecosystems (including seasonally inundated savanna) surrounding the Ranger Project Area, and how do they vary spatially and temporally? ESR1B. Which structural indicators should be used to measure revegetation success?
	ESR2. Determining the requirements to support a terrestrial faunal community similar to areas surrounding the Ranger Project Area.	ESR2A. What faunal community structure (composition, relative abundance, functional groups) is present in the areas surrounding the Ranger Project Area? ESR2B. What habitat, including enhancements, should be provided on the rehabilitated site to ensure the colonisation of fauna, including threatened species? ESR2C. What is the risk of feral animals (e.g. cats and dogs) to faunal colonisation and long-term sustainability?
Long-term viability	ESR5. Assessing the agreed end states for long-term viability and ecosystem function of the restored ecosystem through models and associated sustainability measures	ESR5A. What are the key sustainability indicators to be used to measure restoration success? ESR5B. What are possible/agreed restoration trajectories (flora and fauna) that would ensure the rehabilitated site will move to a sustainable ecosystem without further management intervention which is significantly different from that of the surrounding natural ecosystems?
	ESR6. Understanding the impact of contaminants on vegetation establishment and sustainability	ESR6B. Based on the structure and health of vegetation on the Land Application Areas, what species appear tolerant to the cumulative impacts of contaminants and other stressors over time?

Environmental requirement link	Key Knowledge Need (KKN)	Questions
	ESR7. Understanding the effect of waste rock properties on ecosystem establishment and sustainability	ESR7A. What is the potential for plant available nutrients (e.g. nitrogen and phosphorus) to be a limiting factor for sustainable nutrient cycling in waste rock?
		ESR7B. Will sufficient plant available water be available in the final landform to support a mature vegetation community?
		ESR7C. Will ecological processes required for vegetation sustainability (e.g. soil formation, reproduction) occur on the rehabilitated landform?
		ESR7D. Are there any other properties of the rehabilitated site that could be attributed to any observed impairment of ecosystem establishment and sustainability, including vegetation and key functional groups of soil fauna?
	ESR8. Understanding fire resilience and management in ecosystem restoration	ESR8A. What is the most appropriate fire management regime to ensure a fire resilient ecosystem on the rehabilitated site?
	ESR9. Developing best-practice monitoring methods for ecosystem restoration	ESR9A. How do we optimise methods to measure revegetation and faunal community structure and sustainability on the rehabilitated site, at a range of spatial/temporal scales and relative to the areas surrounding the Ranger Project Area?

Note: ESR is a code used for the KKN and is an abbreviation for ecosystem restoration.

6 Current research into deriving metrics

With progressive rehabilitation and revegetation activities underway at Ranger mine site, measures for the ecosystem similarity goals for the ecosystem restoration standard are currently being derived. Draft faunal closure criteria have been provided by the National Environmental Science Programme's Northern Australia Environmental Resources Hub (Andersen 2019). Recommended faunal closure criteria have been provided for vertebrates, invertebrates and exotic species, along with attributes to be measured (species diversity, species composition, functional diversity and species occupancy). A sampling methodology for assessing the faunal criteria has also been provided.

The provision of attribute measures for reference vegetation communities is being undertaken in a phased approach. Firstly the reference ecosystem has been defined through the selection of appropriate reference sites to meet the Environmental Requirements (Whiteside et al. n.d.). The reference sites were selected based on land units described as "undulating upland terrain" (Wells 1979) which meet the slope characteristics of the final landform design of Ranger and the shallow slope land units surrounding Ranger. It should be noted that there is no reference in the surrounding environment for the waste rock substrate, though trials to date indicate that vegetation from the adjacent landscape can grow successfully on this substrate. We have established 12 savanna reference sites (1 ha each) within a 10 km radius of the mine site to meet the 'adjacency' component of the Environmental Requirements. We are currently establishing four seasonally inundated savanna reference sites to characterise those areas that may be wetter (e.g. toe slopes) post rehabilitation. The Ausplots Rangelands survey protocol has been used to collect species cover data in these 1 ha sites. Additionally, stem density for each species and diameter at breast height (DBH) for every tree in the reference sites have been measured where both of the following criteria have been met: (i) top of the canopy was greater than 2 m in height; and (ii) DBH was greater than 3 cm.

Measures that may be used as indicator values in the ecosystem restoration standard and the supporting data collected have been made available to the mine operator and stakeholders through a series of technical advice documents (Supervising Scientist 2019a, 2019b, 2019c). Existing and accruing knowledge on the ability of the landform and its edaphic properties to support the plant communities (or species therein) and their characteristics inherently defined in these measures will be used to assess, and if necessary, refine the values for regulatory purposes (i.e. closure criteria). Some of these measures are summarised in the following subsections.

6.1 Species richness

A total number of 291 species were recorded across all 12 sites, with 226 being classed as understorey and 65 being classed as overstorey, indicating that species richness is largely dominated by the understorey. Species richness ranged from 62–112 per plot with an average of 91 species per plot (26 average overstorey, 65 average understorey) (Supervising Scientist 2019a).

6.2 Species composition

Total stem densities per plot ranged from 310–1966 stems per hectare, with an average of 826 (Table 4). Table 4 lists all species, ranked from most to least abundant, based on average stem density. Total overstorey cover ranged from 11.1–47.6% and was on average 32.7% across all plots. Of the 65 overstorey species, 7 species made up 80% of the total overstorey cover (i.e. 80% of 32.7%). Figure 2 shows the average cover for the top 10 species. Total understorey cover ranged from 54.8–84.4% and was on average 75.1% across all plots. Of the 226 understorey species, 17 of these made up 80% of the total understorey cover (i.e. 80% of 75.1%). Furthermore, nine species made up 70% of the total understorey cover, indicating dominance across the landscape of a small number of understorey species (Supervising Scientist 2019a).

Table 4 Stem densities for all overstorey species. Trees were counted if the diameter at breast height was greater than 3 cm and the individual was taller than 2 m. Multi-stemmed individuals are regarded as a single stem count. Species marked with a * make up 90% of the total stem density count across all plots. Average column (Table 4a) shows means of all 12 plots (± standard error). Range column (Table 4b) shows the minimum and maximum stem densities across all plots for species with an average stem density of less than 10 per hectare (continued next page)

Table 4a	Stem density (per hectare)											
Species	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	G1	G2	Average (± S.E.)
Plot total	486	1,966	1,388	425	451	404	567	310	670	723	839	1,684	826 (158)
*Acacia mimula**	36	597	421	1	80	183	18	34	354	104	241	203	189 (54)
*Eucalyptus tetrodonta**	150	187	173	119	110	66	234	61	63	238	80	208	141 (19)
*Eucalyptus miniata**	8	197	200	87	30	71	41	13	45	174	31	10	76 (21)
*Corymbia porrecta**	75	180	79	45	30	4	54	42	32	21	84	11	55 (14)
*Xanthostemon paradoxus**	108	10	54	14	16	–	–	44	29	14	124	232	54 (21)
*Corymbia bleeseri**	7	384	154	–	–	–	–	31	–	–	1	13	49 (44)
*Livistona humilis**	14	282	206	–	1	–	–	1	2	–	5	6	43 (33)
*Terminalia ferdinandiana**	20	29	48	5	29	6	43	28	11	10	30	97	30 (7)
*Corymbia foelscheana**	–	–	–	–	–	–	–	–	–	–	40	315	30 (56)
*Erythrophleum chlorostachys**	17	41	18	48	18	25	84	5	7	20	11	27	27 (6)
*Terminalia pterocarya**	–	–	–	–	–	–	–	–	–	–	30	148	15 (24)
Dead (no ID)*	25	15	11	9	14	23	10	6	34	12	11	7	15 (2)
*Persoonia falcata**	–	13	9	6	3	21	9	6	53	37	2		13 (5)
*Buchanania obovata**	3	8	4	11	15	2	3	20	9	4	18	59	13 (5)

Table 4b	**Stem density (per hectare)**												
Species	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**G1**	**G2**	**Range**
Cochlospermum fraseri	2	–	–	18	–	–	11	–	–	–	15	103	0–103
Corymbia disjuncta	–	–	–	–	–	–	–	–	–	–	33	72	0–72
Eucalyptus tectifica	–	–	–	–	–	–	–	–	–	–	26	68	0–68
Acacia lamprocarpa	–	–	–	3	83	–	–	1	–	–	–	–	0–83
Acacia oncinocarpa	–	–	–	–	–	1	3	–	–	50	–	–	0–50
Brachychiton megaphyllus	2	5	1	4	2	–	21	2	–	–	4	12	0–21
Planchonia careya	–	–	–	–	2	–	2	–	–	2	30	14	0–30
Planchonella arnhemica	–	6	4	–	–	–	5	–	12	3	3	7	0–12
Grevillea decurrens	–	–	–	–	–	–	–	3	–	–	12	24	0–24
Pandanus spiralis	–	–	–	6	–	–	22	5	–	–	–	1	0–22
Gardenia megasperma	9		1	1	7			4			2	7	0–9
Acacia dimidiata	–	–	–	–	–	–	–	1	1	21	–	–	0–21
Croton arnhemicus	–	9	2	–	–	2	–	2	–	–	1	2	0–9
Terminalia grandiflora	–	–	–	17	–	–	–	–	–	–	–	–	0–17
Hakea arborescens	–	–	–	–	–	–	–	–	–	–	–	13	0–13
Calytrix exstipulata	4	–	–	3	3	–	–	–	–	–	–	1	0–4
Ficus aculeata	–	–	–	5	–	–	–	–	–	–	–	6	0–6
Stenocarpus acacioides	2	3	–	2	–	–	–	–	–	–	–	4	0–4
Acacia hemignosta	–	–	–	–	–	–	–	–	1	–	–	9	0–9
Owenia vernicosa	–	–	2	–	–	–	–	–	2	5	–	–	0–5
Syzygium eucalyptoides subsp. *eucalyptoides*	–	–	–	–	–	–	–	–	8	1	–	–	0–8
Syzygium eucalyptoides subsp. *bleeseri*	–	–	–	5	–	–	3	–	–	–	–	–	0–5
Acacia platycarpa	–	–	–	–	–	–	–	–	–	7	–	–	0–7
Denhamia obscura	–	–	1	5	1	–	–	–	–	–	–	–	0–5
Petalostigma pubescens	–	–	–	7	–	–	–	–	–	–	–	–	0–7
Grevillea mimosoides	–	–	–	–	–	–	–	1	–	–	5	–	0–5
Acacia humifusa	–	–	–	–	–	–	–	–	4	–	–	–	0–4
Corymbia polysciada	–	–	–	–	–	–	4	–	–	–	–	–	0–4
Grevillea pteridifolia	–	–	–	–	3	–	–	–	1	–	–	–	0–3
Calytrix achaeta	3	–	–	–	–	–	–	–	–	–	–	–	0–3
Corymbia polycarpa	–	–	–	–	3	–	–	–	–	–	–	–	0–3
Dolichandrone filiformis	1	–	–	–	–	–	–	–	–	–	–	2	0–2
Brachychiton diversifolius	–	–	–	2	–	–	–	–	–	–	–	–	0–2
Capparis umbonata	–	–	–	–	–	–	–	–	–	–	–	2	0–2
Corymbia ferruginea	–	–	–	–	–	–	–	–	2	–	–	–	0–2
Vitex acuminata	–	–	–	2	–	–	–	–	–	–	–	–	0–2
Coelospermum reticulatum	–	–	–	–	1	–	–	–	–	–	–	–	0–1
Corymbia dunlopiana	–	–	–	–	–	–	–	–	–	–	–	1	0–1
Syzygium suborbiculare	–	–	–	–	–	–	–	–	–	1	–	–	0–1

6.3 Total basal area

Total basal area per plot ranged from 3.2–10.1 m^2 ha^{-1} with an average of 7.5 m^2 ha^{-1}. Figure 2 shows the average basal area for the top 10 tree species from the reference plots. 7 species made up 80% of total basal area (i.e. 80% of 7.5 m^2 ha^{-1}), with 11 species accounting for 90% of total basal area. Both dominant eucalypt species (*Eucalyptus tetrodonta* and *Eucalyptus miniata*) contributed on average 53% of total basal area across all plots (Supervising Scientist 2019b).

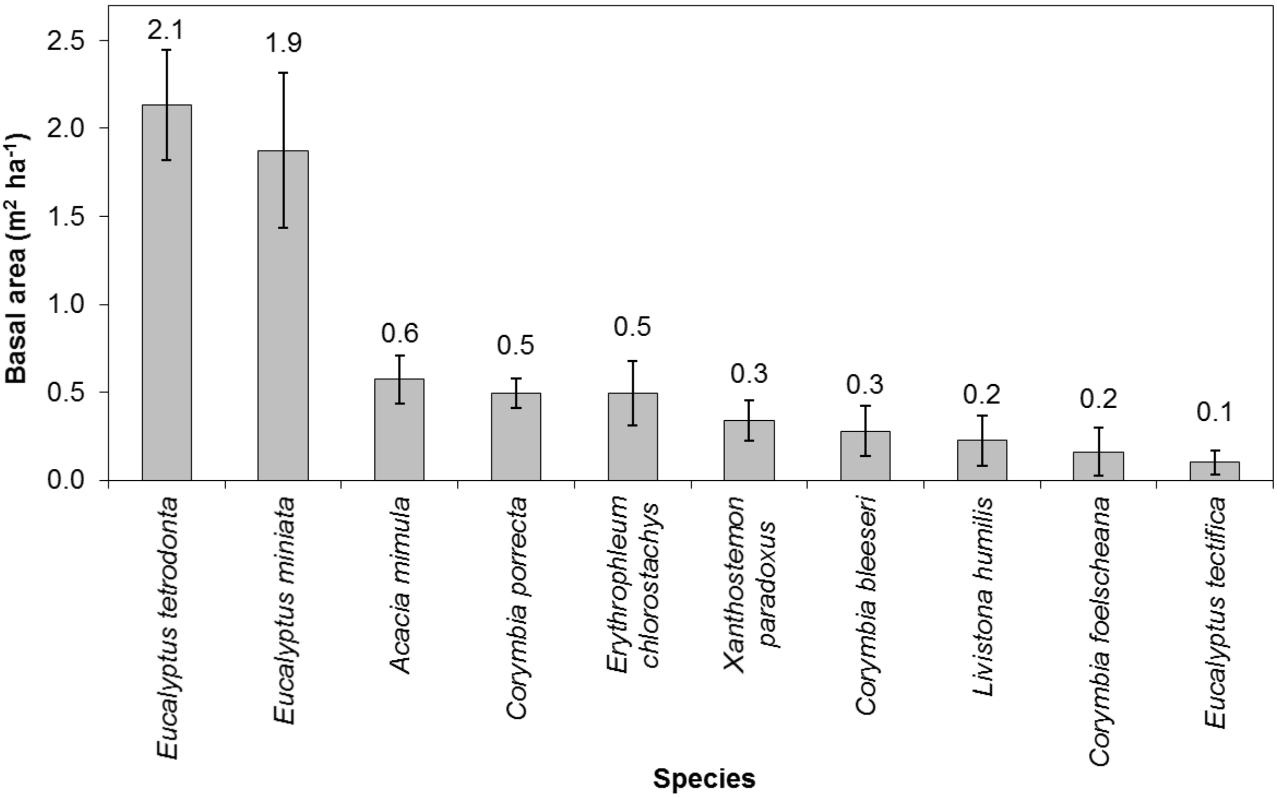

Figure 2 Basal area of top 10 most abundant tree species. Data shown are means, ± standard error. Data calculated from diameter at breast height measurements of trees greater than 3 cm in diameter at breast height and 2 m in height

6.4 Canopy cover

Historical data in the form of aerial photography and high resolution satellite imagery available for 10 dates (1950–2016) were used to derive measures of canopy cover both spatially and temporally. The analysis was conducted on 4,000 x 1 hectare cells and represents our first attempt at deriving an indicator value at a landscape scale. The frequency distribution of percentage cover per ha is similar for each year with most years having a peak in the 30-40% cover class The indicator value (the range) for canopy cover is based on the frequency distribution of median cover per cell for all dates in the temporal period. Figure 3 shows the frequency distribution of canopy cover. The distribution peak (over 27 %) is a median percentage cover of 30-40 %. A distribution of canopy cover that fits within the 1st and 3rd quartile would be statistically similar to the median distribution based on a Kolmogorov-Smirnov test.

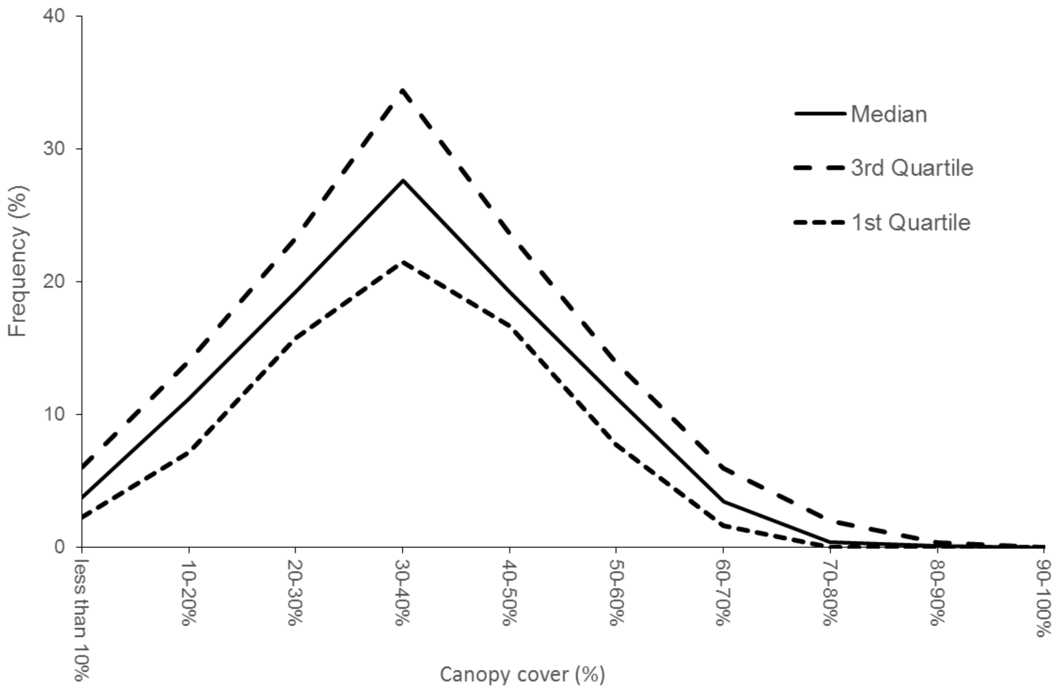

Figure 3 Frequency distribution of median canopy cover for all dates (with 1st and 3rd quartiles) per ha for the area adjacent to Ranger Uranium Mine

6.5 Scaling of indicator values to whole-of-site

The next phase in deriving the attribute measures focuses on the use of remote sensing approaches (where possible) to obtain these measures at the scale of the Ranger rehabilitation (approximately 950 hectares). The reference sites are being used to ground truth drone data. To date we have collected LiDAR, multispectral and hyperspectral data over our reference sites at spatial resolutions of less than 10 cm. Research has been completed on characterising woody canopy cover and how it varies over time using historical aerial photography at the scale of the reference ecosystem (focused on the relevant land units). The effect of scale on closure metrics is currently being assessed through focused effort on two of the reference sites where historical sampling had been undertaken using 20 m x 20 m plots (Erskine et al. 2019).

7 Conclusion

The Supervising Scientist's rehabilitation standards quantify the rehabilitation objectives and recommend specific values based on the best available science that will ensure a high level of environmental protection, and in the case of ecosystem restoration, a highly similar and sustainable ecosystem when compared with the adjacent environment. These values can be used to assess the achievement of, or progress towards, the rehabilitation objectives, some of which may not be reached for a significant period of time.

This ecosystem restoration rehabilitation standard focuses not just on revegetation success, but on all aspects of ecosystem restoration including ecological function, through assessment of key ecosystem processes. It is also linked to the landform stability standard because successful ecosystem restoration will require a stable, non-eroding landform, and conversely a stable landform is predicated on healthy vegetation and associated ecological processes to minimise erosion and gully formation.

Until it can be determined that the rehabilitation objectives have or will be reached, there will be an ongoing need to ensure the ecosystem is on an acceptable restoration trajectory during and after rehabilitation, through continued monitoring, including the comparison of the mine site ecosystem with a reference ecosystem and modelled trajectories for ecosystem restoration.

Acknowledgement

Many thanks to John Woinarski and Kingsley Dixon for their review and contribution to the development of the ecosystem restoration standard. We also thank the field teams from The Centre for Mined Land Rehabilitation, The University of Queensland (Lorna Hernandez-Santin and Natasha Ufer), and the CSIRO (Jon Shatz and Shaun Levick).

References

Andersen, AN 2019, *Faunal closure criteria for the rehabilitation of Ranger Uranium Mine*, Charles Darwin University, Darwin.

Commonwealth of Australia 1978, *Environment Protection (Alligator Rivers Region) Act 1978*, viewed 9 June 2019, https://www.legislation.gov.au/Details/C2004C00290

Department of Environment and Heritage Protection 2014, *Rehabilitation requirements for mining resource activities,* ESR/2016/1875 (formerly EM1122), Brisbane, viewed 2 April 2019, https://www.ehp.qld.gov.au/assets/documents/regulation/rs-gl-rehabilitation-requirements-mining.pdf

Department of the Environment and Energy 2018, *Key Knowledge Needs for Ranger Uranium Mine*, Australian Government, https://www.environment.gov.au/science/supervising-scientist/publications/ssr/key-knowledge-needs-2018

Department of the Environment and Heritage 1999, *Environmental requirements of the Commonwealth of Australia for the operation of the Ranger Uranium Mine*, Canberra.

Energy Resources of Australia Ltd 2018, *Ranger Mine Closure Plan*, viewed 2 April 2019, http://www.energyres.com.au/sustainability/closureplan/

Environmental Protection Authority 2006, *Rehabilitation of Terrestrial Ecosystems (GS6)*, Government of Western Australia, Perth, viewed 2 April 2019, http://www.epa.wa.gov.au/policies-guidance/rehabilitation-terrestrial-ecosystems-gs-6

Erskine, PD, Bartolo, R, McKenna, P & Humphrey, C 2019, 'Using reference sites to guide ecological engineering and restoration of an internationally significant urnaium mine in the Northern territory, Australia', *Ecological Engineering*, vol 129, pp. 61–70.

Garde, M 2015, *Closure Criteria Development—Cultural*, Darwin.

Society for Ecological Restoration 2016, *National Standards for the Practice of Ecological Restoration in Australia*, viewed 2 April 2019, http://www.seraustralasia.com/standards/home.html

Supervising Scientist 2019a, *Technical Advice 006: Species richness and composition indicator values for assessing ecosystem similarity for savanna woodland*, Darwin.

Supervising Scientist 2019b, *Technical Advice 007: Vegetation strata, woody plant species size class distribution and total basal area data for use as indicator values*, Darwin.

Supervising Scientist 2019c, *Technical Advice 008: Canopy cover indicator value for assessing ecosystem similarity for savanna woodland*, Darwin.

Supervising Scientist 2018a, *Rehabilitation Standards for the Ranger Uranium Mine*, viewed 9 June 2019, https://www.environment.gov.au/system/files/resources/eac1374f-538b-488b-bc70-7b23c83ad75c/files/rehabilitation-standards-ranger-uranium-mine.pdf

Supervising Scientist 2018b, *Ecosystem Restoration – Rehabilitation Standard for the Ranger Uranium Mine (version 1)*, viewed 9 June 2019, https://www.environment.gov.au/system/files/resources/eac1374f-538b-488b-bc70-7b23c83ad75c/files/ecosystem-restoration-rehab-standard-ranger-uranium-mine.pdf

Supervising Scientist 2018c, *Landform Stability – Rehabilitation Standard for the Ranger Uranium Mine (version 1)*, viewed 9 June 2019, https://www.environment.gov.au/system/files/resources/eac1374f-538b-488b-bc70-7b23c83ad75c/files/landform-stability-rehab-standard-ranger-uranium-mine.pdf

Wells, MR 1979, *Soil studies in the Magela Creek catchment 1978, Part 1,* Territory Parks and Wildlife Commission, Darwin.

Whiteside, TG, Esparon, AJ & Bartolo, RE n.d., 'A semi-automated approach for quantitative mapping of woody cover from historical time series aerial photography and satellite imagery', Ecological Informatics, submitted for publication.

Williams, AV, Nevill, PG & Krauss, SL 2014, 'Next generation restoration genetics: applications and opportunities', *Trends in Plant Science,* vol. 19, no. 8, pp. 529–537.