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The use of analogue sites for native ecosystem mine rehabilitation—a case study incorporating effective approaches for selection, monitoring and analysis

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Abstract

Evaluating the success of any native ecosystem rehabilitation requires its careful comparison to a desired target. In mine rehabilitation, these targets are often native vegetation communities that were present pre-mining or in the surrounding landscape. Field monitoring plots representative of these community targets are known as analogue or reference sites and are widely used in rehabilitation efforts, yet there is a dearth of literature available on their effective use in mining contexts. Using Whitehaven Coal's rehabilitation operations as a case study, we explore considerations for effective analogue site selection, monitoring and data analysis in the context of native ecosystem mine rehabilitation. To identify the most appropriate targets for the existing or desired mature rehabilitation at Whitehaven operations, an evaluative comparison of landform pattern, location, floristic and structural similarity between the rehabilitation areas and native vegetation communities was conducted. After accounting for operation-specific mine rehabilitation objectives, the best matching candidate communities, based on landscape and rehabilitation context, were selected as final targets. Spatially replicated analogue sites, representing the best-on-offer examples of the targeted ecological community, were established and subjected to an ongoing monitoring program focused on appropriate characterisation of the communities, given temporal and spatial variations in species cover and detectability that occur in the targeted woodland ecosystems. This variability is captured through multiyear resampling of a subset of analogue sites, thereby efficiently providing quantitative data on climatic responses to community composition. The resultant multi-year 'library' of analogue site data allows calculation of analogue benchmark values that can be adapted to provide evolving, dynamic benchmarks, for example, by using the most appropriate subset of current and historical data reflective of contemporary climatic conditions. Methods to calculate these benchmarks encompass averaging replicated site data across climatically similar years but may be extended to complex techniques such as ordination or hierarchical Bayesian modelling. Overall, methods to enhance mine rehabilitation success are urgently required, and to help achieve this goal, we provide a process framework for the use of analogue sites in mine rehabilitation.

Keywords: mine rehabilitation, native vegetation, reference ecosystem, ecological monitoring

1 Introduction

Reference ecosystems are widely used in ecosystem rehabilitation planning and for the evaluation of rehabilitation success (Derhé et al., 2016; Humphries 2015; Suding 2011); such usage is considered to be a core principle in ecosystem rehabilitation science (Anderson 2002). For mining companies, legislation may condition asset relinquishment upon the successful rehabilitation of disturbed areas to communities analogous to a reference ecosystem, which is commonly a specifically nominated vegetation community or structural type. Success is often measured through comparisons of quantitative metrics of community composition, structure, and function obtained through field surveys of nominated vegetation communities with similar metrics obtained from rehabilitation monitoring (Chambers et al., 1994; Doley and Audet, 2013; Kollmann et al., 2016). Hereafter, we use the term 'target community' to refer to a nominated reference vegetation community, encompassing all spatial and temporal variations, and the term 'analogue sites' to refer to a set of monitoring plots selected to represent the target community.

Whilst there has been an ongoing debate around the use of target communities and how to define success in rehabilitation efforts (Doley and Audet 2013, 2016; Erskine et al. 2019; Gwenzi, 2021; McCaffrey et al. 2017), mine operators must adhere to regulatory requirements and so must strive to meet rehabilitation plan objectives within these bounds. A leading practice for native vegetation mine rehabilitation is to select a specific and narrowly-defined native vegetation community and aim to establish rehabilitation that reflects its structural, functional, and compositional characteristics (Lamb et al., 2015; Spain et al. 2023; Young et al. 2022). Owing to the costs and challenges present at all stages of a rehabilitation program, from an early stage mine rehabilitation practitioners should ensure that the most appropriate targets are set and that an effective monitoring program is initiated. The choice of target community can have important ramifications for rehabilitation outcomes. The underlying principle is that specific, naturally-evolved and existing groups of co-existing species are proven to be adapted to fit their environment, so, by best matching these communities to rehabilitation site conditions, the desired outcome of eventuating self-sustaining communities that contribute to wider conservation and ecological function goals will be more obtainable (Cooke & Johnson 2002; Gastauer et al. 2019; Gould 2012; Guimarães et al. 2013).

Target community selection can be influenced by environmental, social, and practical considerations. Ideally, the target community should be the native vegetation present at a site prior to its disturbance, or alternatively the best matching community presented by the surrounding landscape for the desired post-mining landform and its environmental attributes (Humphries, 2015; Spain et al. 2023a; Tischew et al. 2014; Vickers et al. 2012). In some cases, target communities may be located further afield, where these are a better match for rehabilitation site conditions (Cooke and Johnson, 2002; Howard et al. 2011; Lundholm and Richardson, 2010). In mining contexts, target communities may be mandated by regulatory and planning considerations, for example, in order to provide habitat for specific desired species. Practical considerations may also need to be taken into account, for instance due to species propagation issues or conservation risks associated with sourcing sufficient propagules (Broadhurst et al., 2015; Erskine et al., 2019; Hancock et al., 2020; Vickers et al., 2012). Through monitoring, the selected target community informs all stages of vegetation rehabilitation, from species mixes and planting densities, progress tracking, and ultimately, project success.

Target community monitoring should generate datasets that adequately encompass ecological variation, using a sampling methodology that takes into account resolution, extent and temporal considerations (Humphries, 2015; White and Walker 1997), and avoids spatial autocorrelations (Legendre 1993). Despite the importance of monitoring, published guidelines for mine rehabilitation practitioners often provide only broad principles (Lechner et al. 2018), and there remains a knowledge gap in linking principles to practice. While addressing ecosystem restoration more broadly rather than specifically mine rehabilitation, Oliver et al. (2022) examines contrasting Australian restoration case studies that develop standard methods for defining the target ecosystem and selecting analogue sites, focusing on the acceptable range of variation within the desired reference state. For an aquatic post-mine ecosystem (pit lakes) the case study of van Etten et al. (2013) also considers how to choose analogue sites and emphasises the importance of taking into account the environmental drivers of vegetation community structure and dynamics. Monitoring results also require careful analysis and interpretation to deliver maximum value to a rehabilitation project through informing management actions. Well-planned methods are more likely to be cost-effective in the long run

(White & Walker 1997) and may translate into more successful outcomes that not only enhance rehabilitation but also benefit a company’s social licence to operate and the local community's amenities.

Target community selection and the establishment of analogue sites should ideally occur during the mine planning stage (Loch and Lowe 2008; Young et al. 2019), so that rehabilitation goals can be set, and monitoring results can be incorporated into the rehabilitation plan. In practice, this is seldom achieved, so the rehabilitation and monitoring plan (including the target community type) may require subsequent modification to ensure that it is meeting objectives. Here, we look at approaches for implementing analogue site monitoring programs with the aim of incorporating effective workflows and evidence-based principles, using Whitehaven Coal’s rehabilitation operations as a case study. In this context, we discuss relevant considerations and key lessons for selecting suitable target communities, site establishment and replication, metrics to monitor, their analysis and their application to rehabilitation programs.

2 Whitehaven Coal's rehabilitation operations

This case study examines six of Whitehaven Coal's Open Cut rehabilitation operations located in the Gunnedah Basin of New South Wales, Australia (Figure 1). The Tarrawonga and Werris Creek mines are both in the operational phase, with progressive rehabilitation being undertaken. Rocglen, Sunnyside, and three historical ‘legacy’ mines (Melville Open Cut, Springfield, Brickworks) situated on Consolidated Coal Lease 701 (CCL701) are in the rehabilitation-only phase, and Canyon is in closure phase. All are situated in the Brigalow Belt South bioregion, except for Werris Creek, which is in the adjacent Nandewar bioregion. The surrounding native vegetation is dominated by eucalypt woodlands and grasslands, but has been extensively impacted by agriculture, particularly on the Liverpool Plains, resulting in some woodland and grassland communities being listed as threatened (Dunn & Sahukar 2002). The region is characterised by a subhumid climate, having no distinct dry season and a hot summer (Dunn & Sahukar 2002).

Native vegetation rehabilitation was initiated in 2004 at Canyon, in 2007 at Tarrawonga and Werris Creek, and in 2010, 2013, and 2019 respectively for Sunnyside, Rocglen, and CCL701. Native vegetation establishment methods have encompassed seeding, tubestock planting, and spreading of stockpiled salvaged topsoils. Seed mixtures included both native and exotic grass species to assist in soil stabilisation, and from 2021, incorporated a greater diversity of woodland species, and small patches of direct return topsoil at Tarrawonga. As a result of this, and likely due also to drought effects from 2017–2019, species composition and planting densities vary according to the age of each rehabilitation area. Older rehabilitation may also have accumulated volunteer species migrating from the surrounding areas, which tend to represent a mix of agricultural and native vegetation conservation land uses. Native vegetation rehabilitation targets for each mine varied in specificity, from narrowly defined (e.g., ‘Plant Community Type [PCT] 1383—NSW DPE 2022a’) to broadly defined communities (e.g., ‘woodland analogous to adjacent remnant vegetation’), and, in some cases, targets consisted of threatened ecological communities or were unnominated.

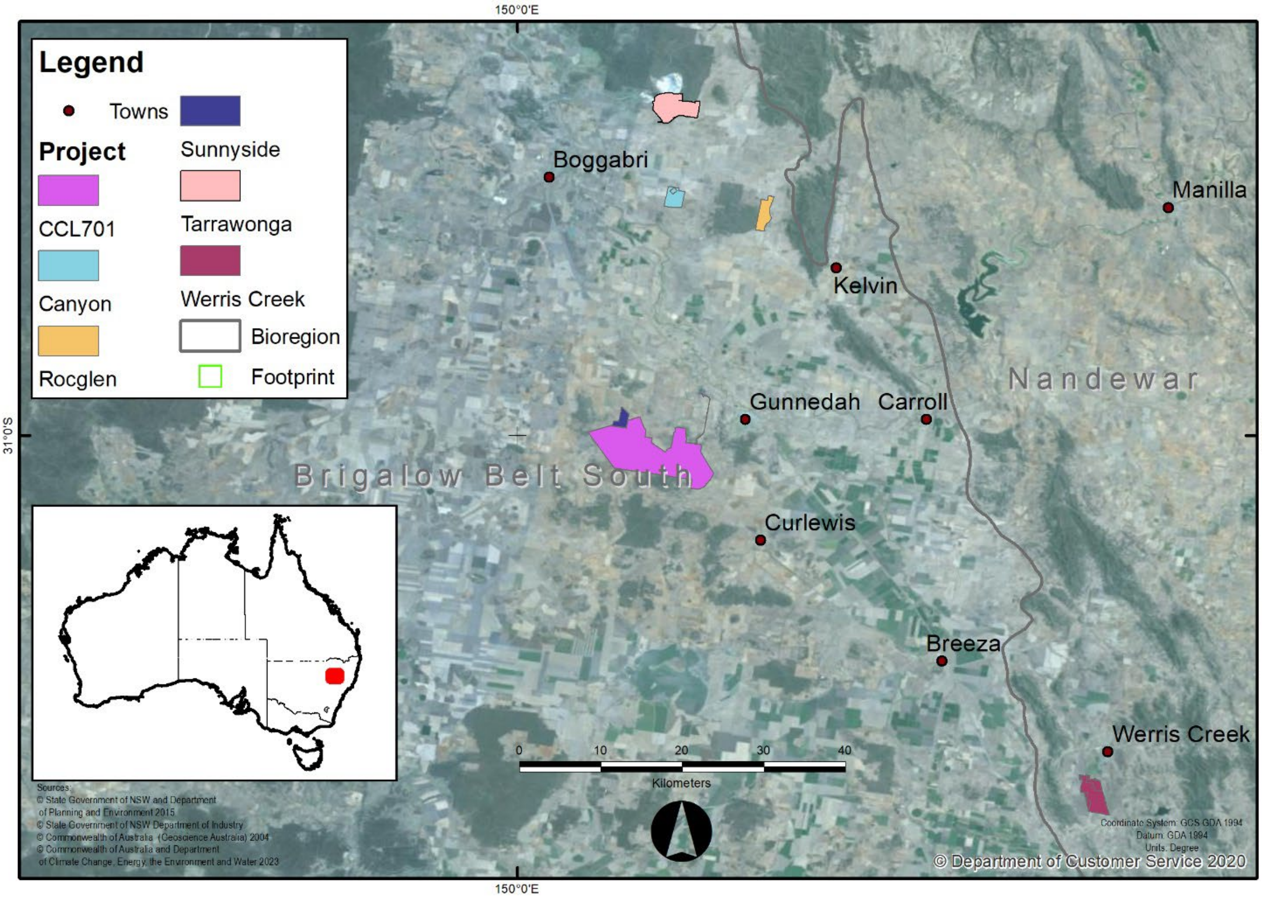


Figure 1 **Case study area showing Tarrawonga, Werris Creek, Rocglen, Werris Creek and Sunnyside, CCL701 and Canyon rehabilitation projects**

3 Implementation of the analogue site monitoring program

We used a four-stage approach to incorporate and monitor new and revised target communities into Whitehaven Coal's rehabilitation operations (Figure 2), which stages we detail in this section. Briefly, in stage one, the planning phase, we reviewed Whitehaven Coal's rehabilitation program to date, in the context of their target community monitoring program and rehabilitation objectives. This informed the need to search for more appropriate targets in some cases. Using a range of data sources (described below), we identified new, more specific or appropriate, target communities (or confirmed the appropriateness of existing ones), and created a map to assist us in locating potential analogue sites in the field. Stage two encompassed fieldwork, using the map to locate and establish replicated analogue sites. Stage three was the monitoring of the analogue sites. In stage four, we analysed the monitoring data to inform rehabilitation actions and progress. Although we here consider these as four discrete stages, in reality they constitute a non-linear framework for the implementation of our target community monitoring, and each must be considered in parallel with the others for program planning and execution (Figure 2).

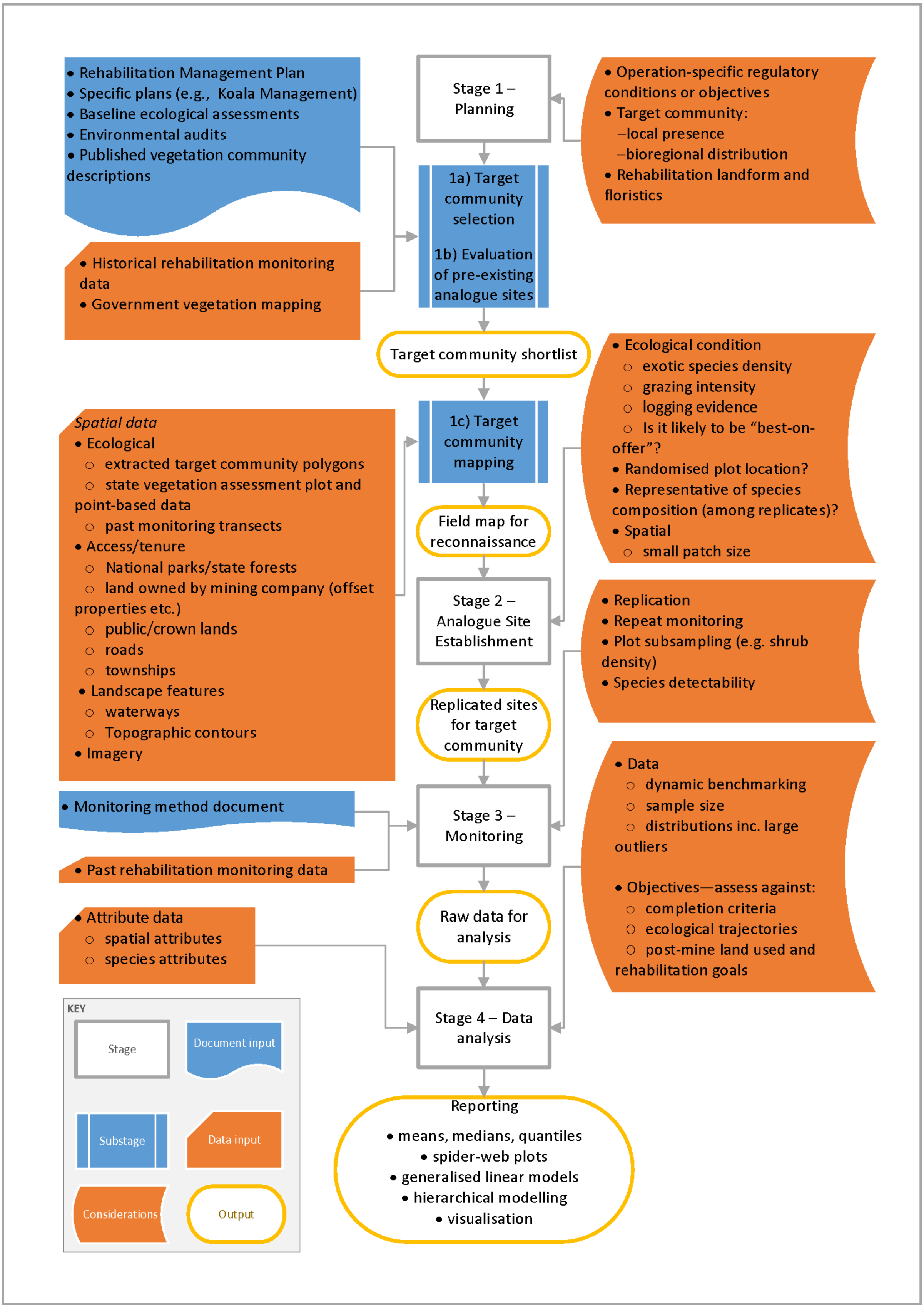


Figure 2 Framework for analogue site monitoring implementation

3.1 Stage 1—planning

3.1.1 Target community selection

Owing to evolving rehabilitation practices and to varying establishment outcomes across years, existing targets needed to be reviewed to ensure they best reflected established communities, broader rehabilitation objectives and regulatory requirements. New targets were also set where these remained unnominated. We used a biogeographical matching approach to select target communities, based on the principle that native mine rehabilitation efforts should preference local and bioregional biodiversity values (Spain et al. 2023a). We initially conducted a desktop review of nominated target communities and rehabilitation objectives for the existing (i.e., vegetated) rehabilitation at Whitehaven operations by comparing rehabilitation monitoring floristic records and topography with published details on the nominated communities. In one instance, the target community specified had been misidentified and was not a community that was locally present. Where a specific target community was unnominated, or the nominated one was found to be unsuitable (for example, due to a habitat not being locally present), we carried out a process to select a suitable target community.

Using published descriptions of local vegetation communities, together with government geospatial vegetation datasets (NSW DPE 2022b, 2023; NSW DPE 2023), a candidate list was created of target communities that occur in landscape positions similar to the rehabilitation areas within the respective mining operations. In creating the candidate list, we only considered communities that occurred within the bioregion of the mine operation (Spain et al. 2023a). In evaluating candidates, operation-specific regulatory conditions or objectives also had to be taken into account, for example, the provision of koala habitat at Sunnyside. We created assessment tables to help select the optimal target among candidate communities. Table 1 is an example from Sunnyside, and includes considerations of mine documentation, local presence, suitability as koala habitat, floristic and structural similarity, landscape similarity, and presence of established monitoring sites. At Sunnyside, after accounting for operation-specific mine closure objectives, PCT589 was selected as the best-matching candidate community, based on landscape and rehabilitation context (Table 1), resulting in an update of the rehabilitation plan. Figure 3a shows a woodland rehabilitation site on a dump slope at Sunnyside coal mine, with the saplings depicted mostly comprising White Box (*Eucalyptus albens*) and Yellow Box (*E. melliodora*), which are dominant and associated, respectively, in PCT589; in the background can be seen the hills and rolling plains representative of the landscape in which PCT589 can be found. Figure 3b shows a nearby analogue site dominated by mature White Box and with a mid-dense ground layer of grasses and forbs. For other rehabilitation sites with existing vegetation, the most closely analogous candidate community was selected as a target by using a combination of rehabilitation planting records, monitoring data, visual site assessments, and landscape context to inform decisions. These same targets were also nominated for any contiguous planned or uninitiated (i.e., unvegetated) rehabilitation. For cases where contiguous uninitiated rehabilitation represented a different landform element, or was discontinuous with other rehabilitation areas, the first principle of biographical matching was applied for target selection.

Table 1 Example candidate analogue target shortlist evaluation—potential woodland targets for Sunnyside Coal Mine

	Plant Community Type ID				
Analogue selection consideration	**101**	**435**	**589**	**592**	**1383**
Nominated mine documentation target	✗	✗	✗	✗	✓
Occurs locally or adjacent to Sunnyside	✓	✗	✓	✓	✗
Known local koala sightings	✓	✗	✓	✓	N/A
Dominated by primary koala feed trees that also dominate the rehabilitation	✗	✓	✓	✓	✓
Sometimes subdominated by primary koala feed trees that also subdominate the existing rehabilitation	✓	✗	✓	✓	✗
More grassy than shrubby, like existing rehabilitation	✓	✓	✓	✗	✓
Similar landscape position to existing rehabilitation	✗	✓	✓	✓	✗
Analogue sites already established or easily established	✗	✓	✓	✓	✗

Figure 3 Photos of monitoring sites at or adjacent to Sunnyside Coal Mine (a) in nine-year-old rehabilitation, and (b) analogue remnant vegetation PCT589

3.1.2 Evaluation of pre-existing analogue sites

For some mines, analogue sites had already been established. Where available, we reviewed site monitoring data to independently validate vegetation community identity against published descriptions (NSW DPI 2022c). This indicated that some sites were recorded as representing vegetation community to which they did not conform, and this was confirmed through site visits using a rapid survey method (NSW OEH 2017). We also examined the density of recorded exotic species as an indicator of site quality, and plot locations to assess issues with accessibility, autocorrelation, and site perpetuity. We found that some sites were in close spatial proximity, whilst others were situated in the footprint of an active mine pit plan, and so were unsuitable for long-term monitoring. Wherever possible we retained existing sites for continued monitoring and discontinued those that were no longer suitable for our goals.

3.1.3 Target community mapping

In preparation for analogue site establishment, we created a field reconnaissance geospatial (GIS) dataset of potentially suitable plot locations for each target community, sourced from publicly available government geospatial vegetation data (NSW DPE 2022b) and land tenure data (NSW DCS 2023), together with data provided by Whitehaven Coal on their property boundaries. We made target community polygons, broadly bounded by a buffered bioregional subregion and narrowly bounded by land tenures that we had permission to access. We removed small (< 5 ha) and highly fragmented community occurrences, and inaccessible polygons, and categorised some polygons as high priority based on inferred quality (for example, occurring within a large conservation reserve) and spatial proximity to rehabilitation operations. For communities with limited occurrences, we individually vetted all polygons for evidence of prior clearing or logging by looking at the spatial patterning of trees in aerial photography; this informed our prioritisation of polygons.

For threatened ecological communities and others with limited occurrences, we also reviewed publicly available State vegetation assessment plot and point-based data (NSW DPE 2013) to evaluate potential sites and their condition. We checked site descriptions for exotic species diversity and abundance, and notes on disturbance, to infer site quality. We also sought government departmental advice to locate examples of targeted threatened ecological communities which were in good condition. All qualified target community and land tenure polygons, together with point locations, were then combined and clipped for use on handheld global positioning systems (GPS) in the field (Figure 2).

3.2 Stage 2—analogue site establishment

Guided by our field reconnaissance maps, we visited target community polygons and points for assessment of vegetation type, condition, and potential plot locations, allocating more time for scouting rare communities. We aimed to establish five replicate sites for each target community, spatially separated by a minimum of one kilometre. These analogue sites were to be used across the different rehabilitation operations where these shared the same target. In some instances, regulatory requirements specified that particular rehabilitation operations must target particular local vegetation (i.e., adjacent to the mine) or a certain structural form (e.g., a threatened grassy woodland variant), so not all sites of the same target community could necessarily be shared; this resulted in operation-specific replication in those instances.

At each location, site condition was visually assessed based on exotic species density, grazing intensity, and logging evidence. Vegetation community type was validated in the field by identifying dominant species and referring to published descriptions. For some threatened ecological communities, structural elements also had to be considered to ensure they met legislated descriptions and condition qualification criteria. We selected sites representative of the target community for monitoring based on the principle of 'best-on-offer' common in Australian monitoring methodologies (Eyre et al. 2017; OEH 2018; White et al. 2012).

For statistical purposes, we randomised plot location within the patch of vegetation using a random number generator for compass bearing and pacing distance. However, in some instances, there was only a limited area or bearing available for a site (e.g., due to small patch size, extensive disturbance impacts, or slope). In these cases, we restricted randomisation within narrower limits, or established the plot in the only feasible location. On one occasion during site selection, we noted that previously established randomised plots representing the target community (PCT592) had failed to capture patchy stands of the associated canopy tree *Alstonia constricta*. For this reason, we restricted randomisation to ensure the patch was partially captured within the plot. Despite extensive search efforts, we were unable to locate five spatially separated, high-quality representatives of a threatened woodland target (PCT599), resulting in some selected sites being narrowly spatially separated (minimum 360 m). These sites differed structurally as regarded the presence of a shrub layer, and although they might exhibit some autocorrelation, this was determined to be outweighed by the benefits of additional sampling. Additionally, one site was found to have high-quality structural characteristics (in terms of woody vegetation maturity and density), but an invaded understory. This was incorporated as a structural replicate only, and groundcover metrics were not recorded. Three replicates were usually established in the first year, and then a further two in the second year.

3.3 Stage 3—monitoring

We developed a uniform annual monitoring program to be applied to both rehabilitation and analogue sites. This program was designed to capture all quantitative data needed for the evaluation of each mine's completion criteria, whilst also providing valuable data for the assessment of ecological trajectories, broader rehabilitation goals, and specific management objectives such as tubestock survival and weed monitoring. We adapted the Biodiversity Assessment Method (BAM—NSW DPIE 2020), a widely used method for state vegetation surveys in NSW, to meet our specific needs whilst still providing data broadly compatible with the NSW state vegetation database. Plots were 50 × 20 m, with a nested 20 × 20 m quadrat, and five 1 m^2 quadrats arranged linearly every 10 m along the plot centre line, for recording woodland structural data, species cover and abundance, and groundcover, respectively. Surveys were conducted during the austral spring and commenced in 2019.

3.3.1 Method outline

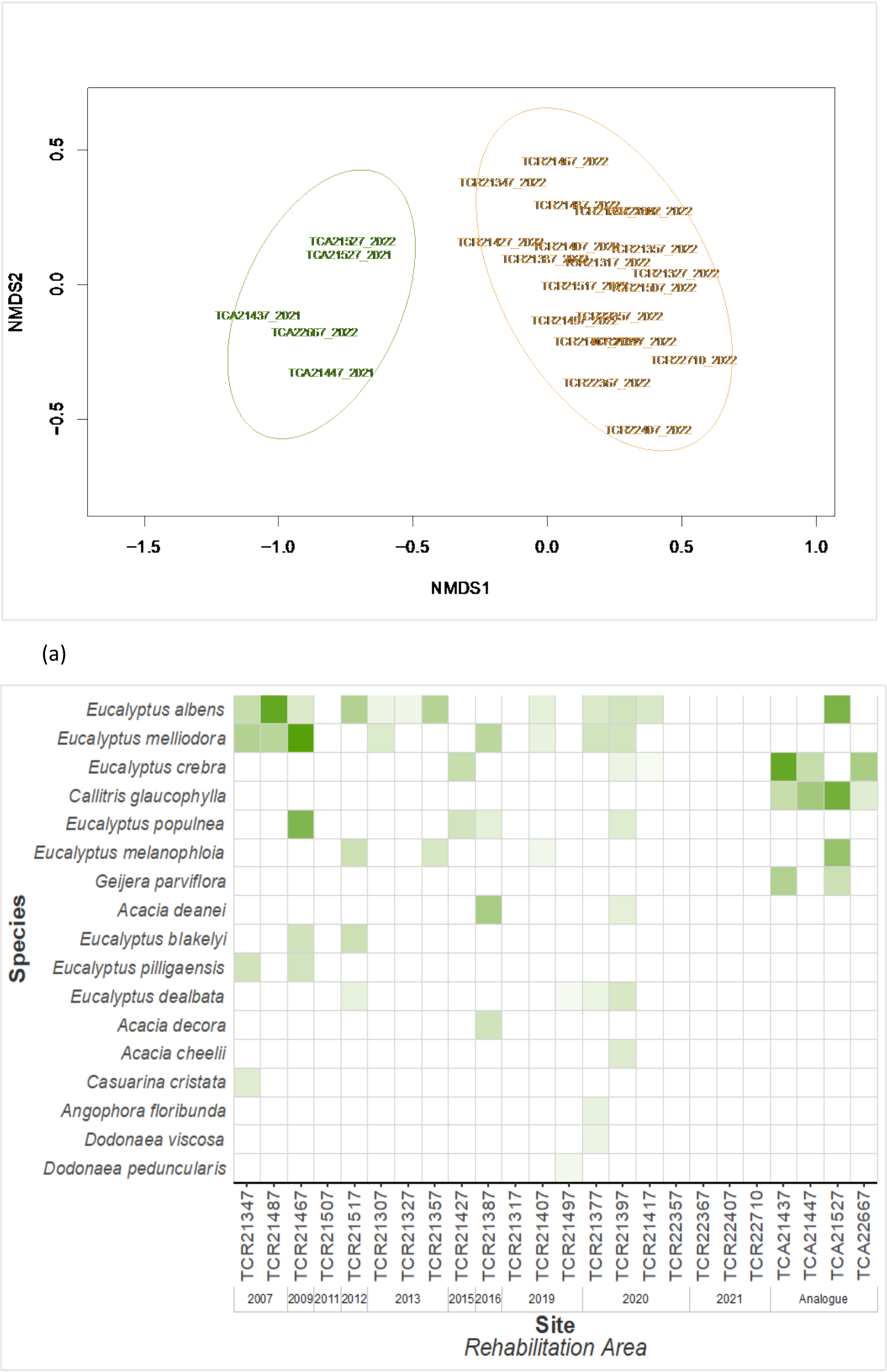
Within each 50 × 20m plot, we recorded all tall (> 2 m) woody plant species densities, heights, basal areas, and all tree seedling (< 2 m tall) species densities. The number of tree hollows was also recorded. A pragmatic approach is often required to measure stem density, particularly for shrubs (Neldner et al. 2022). In shrubby communities, we sub-sampled stem density counts where the total count of all stems across the plot was impractical. In the 20 × 20 m nested quadrat, the percentage canopy cover of each species within each stratum was recorded together with all strata tallied abundances and fertility states. Within each of the five 1 m^2 quadrats, the percentage of groundcover, comprising native vegetation, exotic vegetation, bare ground, and litter was recorded.

3.3.2 Analogue site resampling

To efficiently capture interannual variations in analogue sites, we developed a monitoring program to annually sub-sample established replicate sites. Upon achieving five replicate sites for each target, the annual resampling intensity was reduced to a subset of at least one of the five sites in any one year. As resources for monitoring are finite, monitoring intensity should reflect the rate of change of any pertinent metrics to the objectives of the monitoring program. Within resampled sites, all metrics were recorded apart from basal area, owing to the slow rate of annual change in this metric.

3.4 Stage 4—data analysis

In the first year, all replicate sites for each target were analysed together, to create benchmark data for rehabilitation evaluation against completion criteria. This was done by direct comparison of analogue and rehabilitation mean values for each metric of interest. Bray-Curtis dissimilarity indices provided additional insights into community comparisons and these were tested using permutational multivariate analysis of variance (PERMANOVA) (Figure 4a). We also made heat-map tile plots of species occurrences and relative cover to provide site-level insights into species composition (Figure 4b). To provide a complementary perspective, benchmark values, derived from the results of the NSW government state vegetation survey (NSW DPE 2022c), were also provided for comparison against completion criteria targets. In the following years, we began the creation of annual dynamic benchmarking values—benchmark values created using both the current year and a subset of the earlier data that best matched the contemporary climatic conditions. For example, 2019 was a drought year, while the following years (2020–2022) were wetter than average. For the creation of the 2022 dynamic benchmark values, we excluded the drought year and used only 2020–2022 data. This approach differs from static benchmarking, where a single snapshot is made of the analogue target, and current and future rehabilitation is compared to this value. Similar processes have been used to create large-scale dynamic benchmarks for Australian vegetation communities (Yen et al. 2019). From each replicate site, we obtained mean values across the subset of sampling years, and from this, dynamic benchmark mean values were calculated (so that $n = 5$ for each target). We also performed more detailed statistical testing for some sites where this was a requirement of mine documentation, for example, using generalised linear models with a beta distribution for comparisons of species cover, avoiding the need to transform data for analysis (Douma & Weedon 2019). To visualise community similarity between analogue and rehabilitation sites, we used non-parametric multi-dimensional scaling (NMDS) of Bray-Curtis dissimilarity indices of species occurrence and abundance data (Bray & Curtis 1957; Oliver et al. 2022). An example output is shown in Figure 4a.



(a)

(b)

Figure 4 Example results (from Tarrawonga 2022 monitoring) comparing analogue vs rehabilitation through (a) NMDS ordination of Bray-Curtis dissimilarity; and (b) heat map of canopy species abundance

4 Key lessons and discussion

4.1 Planning

Whitehaven Coal's rehabilitation operations represent a case study of selecting new native vegetation targets and redefining historical targets. Both tasks require careful planning and evaluation to ensure the most appropriate targets are identified. NSW has an extensive, publicly available vegetation classification dataset (Roff et al. 2022) that we were able to leverage for the identification and location of potential target communities. We acknowledge, however, that similar resources may not be available in some regions. In these circumstances, practitioners may have to draw more heavily upon published documents, remote sensing, topographic and soil maps, and local knowledge, in combination with field reconnaissance to identify suitable targets and their locations.

Ideally, the target community should be the pre-disturbance native vegetation community of the rehabilitation site (Spain et al. 2023a). If there is a mismatch between post-mining landforms and this community's requirements, the principle of selecting the most suitable community from the surrounding landscape or bioregion for the specific rehabilitation environmental context should be applied (Spain et al. 2023a). Where appropriate, we tailored target communities to specific topographies within rehabilitation operations, in line with objectives to blend rehabilitation landforms with the surrounding natural environment. Occasionally, target community options may be restricted due to mandated regulatory conditions. In these scenarios, the same principles apply, but within the subset of suitable candidates. In the above situations, and in cases where rehabilitation plantings had already been initiated, tools such as evaluation tables (e.g., Table 1) can assist in determining the optimal target communities and in documenting the rationale for the selection.

Data-driven approaches to target community selection have also been demonstrated, for example, by using intensively sampled field data together with site similarity analyses (Durbecq et al. 2020). One challenge in the use of target community methods is integrating ecotones and patch heterogeneity into rehabilitation plans, which integration should be implemented in light of ecological theory (Jonson 2010). Machine learning can be used for community and species occurrence predictions (Roff et al. 2022), offering possibilities for high-resolution modelling of species associations to be mapped onto rehabilitation landforms. Yet, these tools require large datasets, which will limit their availability to practitioners. With increasing computational power and affordability of technology such as unmanned aerial vehicles, these tools have increasing potential for application to rehabilitation objectives (Buters et al. 2019).

4.2 Analogue site establishment

Locating suitable representatives of the target community can be challenging, especially when these targets are themselves threatened ecological communities. High-quality representatives of these communities are inherently rare, and may only exist as small, disturbed patches; these highlight the need for biosecurity protocols to be followed during any fieldwork. Departure from strict adherence to the site establishment methods may be warranted regarding the location or configuration of plots when patch size is small, for example, by substituting 10 × 100 m plots in place of 50 × 20 m plots to capture linear communities. Randomisation is an essential component for statistical inference, and, when establishing plots, it is desirable to reduce human bias (Glenn et al. 2014). Yet, analogue sites are essential for formulating rehabilitation species mixtures and planting densities; therefore, analogue site selection can have direct repercussions on rehabilitation quality. Very few rehabilitation programs will have the resources for sufficient replication to capture all target community species and spatial variation. Trade-offs may be required in some cases between ideal statistical sampling methods and locating plots for broader monitoring objectives.

Whitehaven Coal rehabilitation operations target sub-humid woodlands. Our sampling methods were derived from NSW state vegetation monitoring methods (NSW DPIE 2020; Sivertsen 2009), which were well-suited for woodland assessment and resulted in data compatibility with government collections, thus benefiting the wider scientific research community. Other regions or vegetation structural types may require different approaches. Numerous vegetation survey methods are available (Spain et al. 2023b), and these should be tailored to best match project needs while maintaining compatibility with state survey methods wherever possible.

Spatial replication is highly labour-intensive, yet sampling design should ensure adequate spatial replication (Glenn et al. 2014). To optimise sampling, a balance should be sought so that plot size captures a high proportion of local diversity, with sufficient replication so that an inflection point of a species accumulation curve is reached (Neldner & Bulter 2008). Methods such as statistical power analysis have also been demonstrated in mine rehabilitation contexts, and the results have been used to formulate goals that consider target community variability (Lechner et al. 2018; Oliver et al. 2022). In practice, replication will often be determined by resource constraints that are apparent in the planning phase. We used five replicates with the knowledge that the target communities tend to be highly diverse; five being the maximum number we could conceivably obtain within project constraints. For threatened ecological communities, finding sufficient spatially separated, high-quality sites, may not be possible, and may require compromises in terms of the risk of spatial autocorrelation or recording all monitoring metrics. In some cases, best-on-offer principles may need to be applied selectively to different structural and compositional elements in order to create partial replicates, excluding any poor-condition elements from analyses.

There is ongoing debate regarding the use of historical benchmarks in restoration ecology (Balaguer 2015; Shackelford et al. 2021). This issue is particularly relevant in the case of threatened ecological communities where many remaining occurrences may exist in a disturbed state, and where the process needed for persistence of the historical state may no longer be intact (Hobbs et al. 2009). The use of best-on-offer target values acknowledges that few terrestrial ecosystems remain totally free of anthropogenic impacts (Landsberg and Crowley, 2004; Thackway and Freudenberger, 2016), but it is important to acknowledge that, in some cases, best-on-offer target values may not align with rehabilitation objectives (Shackelford et al. 2021). In these cases, other sources of data may be required, together with appropriate goal setting. Ultimately, decisions on how to approach and to benchmark rehabilitation of threatened ecological communities will require greater collaboration between policymakers, regulators and practitioners in order to devise appropriate rehabilitation goals with acceptable outcomes.

4.3 Monitoring

Monitoring metrics will depend upon the type of vegetation being rehabilitated and the completion criteria requirements. In addition to providing benchmarking values, monitoring metrics inform rehabilitation actions. Species composition and abundance are fundamental for designing seeding and planting mixtures, and for woody vegetation, structural characteristics such as tree species density can be used to guide tubestock planting density. Recording fertility can assist in seed collection efforts. Other metrics such as counts of hollows and basal area can be used to estimate interim faunal nesting box requirements and allow growth trajectories to be modelled for planning purposes. Occasionally, methods may need to be adjusted, in these situations, but where possible it is important that data remains retrospectively compatible with any prior monitoring methods, in order to preserve the long-term integrity of the monitoring program.

Vegetation communities tend to exhibit both short and long-term temporal variations in their composition, structure, and species detectability (Allen & Benson 2012; Mori 2011; Kéry & Gregg 2003). Most monitoring programs sample when above-ground species diversity is highest or during peak flowering (Neldner et al. 2022; Sivertsen 2009), both of which phases coincided with our monitoring during the austral spring. In our study region, both warm and cool-season grasses and forbs occur (Allen & Benson 2012); these may not be sampled adequately if surveys are restricted to a single season. Studies on grassland communities in the Gunnedah Basin have found that approximately one-third of species recorded in summer were not recorded in spring, and vice versa (Allen & Benson 2012), and a single sampling event may only detect 40–70% of grassland species occurring at a site (Schultz et al. 2014). Furthermore, large seasonal variations in the dominant groundcover species were also observed (Allen & Benson 2012). These seasonal variations are likely to occur across a range of herb-rich environments, yet these variations are rarely considered in vegetation monitoring programs (Gellie et al. 2018). Although we primarily surveyed woodlands having much higher species diversity than surrounding grasslands, this is one limitation of our methodology we aim to address in coming years. At our sites, incomplete data on seasonal groundcover dominance may translate into incorrect planting lists, which potentially has ramifications for the resiliency of the grassy understorey occurring in several of our target communities to exotic invasions (Prober & Lunt 2009). These issues warrant more research by ecosystem rehabilitation scientists.

Monitoring should also account for interannual variability (Lindenmayer & Likens 2018). In a recent review of studies using analogue targets, Shackelford et al. (2008) found that, in 80% of studies, sites were only sampled across one or two years. Inadequate sampling of temporal variability may result in incomplete species detections or overly rigid targets that are difficult to achieve and may limit understanding of the dynamics of community transitions (Schultz et al. 2014; Shackelford et al. 2021). For practitioners, project resource constraints, together with ease of access to sites and site structural complexity, will influence the extent of spatial or temporal replication that can be achieved. One factor in our decision to pursue longer-term analogue site resampling over greater spatial replication was the high investment needed for initial site scouting and plot establishment, given the potential benefits of temporally replicated monitoring. These trade-offs will need to be assessed on a case-by-case basis for a given project.

4.4 Data analysis

The data obtained from our analogue site monitoring informs many rehabilitation actions and serves as a benchmark to measure rehabilitation progress. So far, our analyses have been largely limited to obtaining benchmark mean and standard error values, visualisation of species occurrences in the form of heatmaps, analysis of variance (ANOVA), and community similarity analyses. These four methods respectively require greater familiarity with data analysis but are readily accessible methods to practitioners. One important consideration in using summary statistics for benchmarking is the distribution of the data; for datasets with skewed distributions or large outliers the use of median values is appropriate (Eyre et al. 2017). Quantiles are also commonly used to evaluate rehabilitation against reference data (Humphries 2016). For visual assessment of rehabilitation progress, spider-web plots are a valuable and accessible method (e.g., Neldner & Ngugi 2014). Increasingly, generalised linear models using the beta distribution are being used for modelling plant canopy cover (Damgaard et al. 2019), and we have found these to be valuable tools for examining differences in groundcover and other cover metrics. More complex methods, for example, PERMANOVA, generalised linear mixed modelling, and hierarchical Bayesian modelling (e.g., Oliver et al. 2022; Yen et al. 2022), require more advanced skills but can accommodate more complex experimental designs and research questions. With the expansion of our analogue site dataset in future years, we anticipate greater use of statistical models to calculate dynamic benchmarks and their confidence intervals, explore ecological trajectories, and provide more detailed assessments of community similarity based on life-form and stratum so as to guide rehabilitation management interventions. In addition, progress is underway to explore and extract more value from the analogue site monitoring data so as to refine woody species planting densities and seed mix ratios. These results, and their effective communication to stakeholders, represent a key objective for any effective monitoring program.

5 Conclusion

Target community selection may affect rehabilitation outcomes and broader biodiversity conservation goals, so it is imperative that targets are carefully selected by rehabilitation practitioners. A wide variety of site-specific factors must be considered when choosing optimal targets, and for this reason, there is no one-size-fits-all approach. Choices must be informed by a detailed understanding of regional biogeography, the rehabilitation site's biophysical attributes, and regulatory requirements. Effective monitoring is required to ensure that the target community is adequately and efficiently characterised. Monitoring results inform many aspects of rehabilitation programs, from initiation to completion, and hence provide great value to projects, yet to fully realise this value, data must be carefully explored, analysed, and communicated to stakeholders. Whilst we have strongly advocated for rigorous approaches to target community use, much greater collaboration is required between policymakers, regulators, and practitioners in order to refine the concept of rehabilitation success to ensure goals remain achievable. The science of ecological rehabilitation is still in its infancy, and we hope that this case study will assist practitioners plan emerging projects and stimulate further discussion on the methods and methodologies most appropriate for choosing, monitoring, and applying results of target community use to rehabilitation objectives.

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