8 August 2016

Rehabilitation of Grassy Box Woodland –A structured Review

Richard Thackway and David Freudenberger
FOR
ANU ENTERPRISE PTY LIMITED

Table of Contents

List of Figures page size

List of Tables

Scope and project aims

The aims of this report were to conduct a comprehensive review of the scientific papers and publically available research reports on restoring grassy eucalypt woodlands[1], particularly on mined surfaces. This literature review was complemented by interviews with leading practitioners and visits to rehabilitation sites to rapidly identify issues and inspect techniques relevant to rehabilitating grassy woodlands that may not be documented in the literature. A major objective of this review was to identify key uncertainties in rehabilitating grassy woodlands and to recommend priority research areas to reduce uncertainties in effective rehabilitation practice.

Review Methodology -A conceptual framework approach

First we used the Vegetation Assets States and Transition (VAST) framework (Thackway & Lesslie, 2008) to critically appraise the relevance of scientific studies, reports and on-ground practice for achieving condition-based outcomes relevant to the reconstruction or rehabilitation of plant communities, in particular, grassy woodlands. The VAST framework has been applied to understanding the environmental trajectories of diverse landscapes at multiple scales from national *State of the Environment* reporting to individual mine sites in the Hunter Valley, NSW (Appendix 3).

We acknowledge that in the context of the Mineral Resources Development Cycle (MRDC), phase 5 (production) initially creates a landscape devoid of native vegetation (Appendix 1). The VAST framework (Table 1) thus classifies mined surfaces as “Type VI: *Removed*; Alienation to non-vegetation land use”. We further acknowledge that a great deal of rehabilitation effort and innovative practices are required to transform waste rock emplacements to early phase rehabilitated grassy woodlands (*Transformed*, Table 1). We assume the long-term goal is to transition early stage rehabilitation towards a *Modified* state (Table 1) or an *Unmodified* state. This is a significant challenge as it requires a fundamental scientific understanding of ecological processes and application of appropriate technologies. We review evidence that shows how researchers and practitioners use theory and leading practice techniques to transition landscapes that are devoid of native vegetation (*Removed*; Table 1) toward a *Modified* state and ideally to an *Unmodified* state over time, following mining.

---

[1] White Box-Yellow Box-Blakely’s Red Gum Grassy Woodland and Derived Native Grassland is listed as a critically endangered ecological community under the Environment Protection and Biodiversity Conservation Act 1999 (New South Wales Department of Environment, Climate Change and Water, 2010) and is the focus of this review. For brevity variants of this community are referred to as *grassy woodlands*.

Table 1. Vegetation condition classes and commonly observed characteristics of vegetative systems modified by human activity

Increasing vegetation modification from left to right

		Native Vegetation Cover Dominant structuring plant species indigenous to the locality and spontaneous in occurrence – i.e. a vegetation community described using definitive vegetation types relative to estimated pre1750 types#				**Non-native Vegetation Cover** Dominant structuring plant species indigenous to the locality but cultivated; alien to the locality and cultivated; or alien to the locality and spontaneous		
Vegetation Cover Classes		Type 0: **NATURALLY BARE** Recently naturally disturbed areas where native vegetation has been entirely removed. (i.e. open to primary succession)	Type I: **RESIDUAL /UNMODIFIED** native vegetation community structure, composition, and regenerative capacity intact – no significant perturbation from land use/land management practice	Type II: **MODIFIED** native vegetation community structure, composition and regenerative capacity intact - perturbed by land use/land management practice	Type III: **TRANSFORMED** native vegetation community structure, composition and regenerative capacity significantly altered by land use/land management practice	Type IV: **REPLACED - *ADVENTIVE*** native vegetation replacement – species alien to the locality and spontaneous in occurrence	Type V: **REPLACED - *MANAGED*** native vegetation replacement with cultivated vegetation	Type VI: ***REMOVED*** Alienation to non-vegetation land use.
Diagnostic criteria	Current regenerative capacity	Complete natural removal of in-situ regeneration capacity except for ephemerals and lower plants	Natural regenerative capacity unmodified	Natural regeneration capacity persists under past and /or current land management practices	Natural regenerative capacity limited / at risk under past and /or current land use or land management practices. Rehabilitation and restoration possible through modified land management practice	Regeneration potential of native vegetation community has been suppressed and in-situ resilience at least significantly depleted. May still be considerable potential for restoration using assisted natural regeneration approaches.	Regeneration potential of native vegetation community likely to be highly depleted by intensive land management. Very limited potential for restoration using assisted natural regeneration approaches.	Nil or minimal regeneration potential. Restoration potential dependent on reconstruction approaches.
	Vegetation structure	Nil or minimal	Structural integrity of native vegetation community is very high	Structure is predominantly altered but intact e.g. a layer / strata and/or growth forms and/or age classes removed	Dominant structuring species of native vegetation community significantly altered e.g. a layer / strata frequently and repeatedly removed	Dominant structuring species of native vegetation community removed or predominantly cleared or extremely degraded	Dominant structuring species of native vegetation community removed	Vegetation absent or ornamental
	Vegetation composition	Nil or minimal	Compositional integrity of native vegetation community is very high	Composition of native vegetation community is altered but intact	Dominant structuring species present - species dominance significantly altered	Dominant structuring species of native vegetation community removed	Dominant structuring species of native vegetation community removed	Vegetation absent or ornamental
Examples		Bare mud; rock; river and beach sand, salt and freshwater lakes	Old growth forests; Native grasslands that have not been grazed; Wildfire in native forests and woodlands of a natural frequency and/or intensity	Native vegetation types managed using sustainable grazing systems; Selective timber harvesting practices; Severely burnt (wildfire) native forests and woodlands not of a natural frequency and/or intensity	Intensive native forestry practices; Heavily grazed native grasslands and grassy woodlands; Obvious thinning of trees for pasture production; Weedy native remnant patches; Degraded roadside reserves; Degraded coastal dune systems; Heavily grazed riparian vegetation	Severe invasions of introduced weeds; Invasive native woody species found outside their normal range; Isolated native trees/shrubs/grass species in the above examples	Forest plantations; Horticulture; Tree cropping; Orchards; Reclaimed mine sites; Environmental and amenity plantings; Improved pastures. (includes heavy thinning of trees for pasture); Cropping; Isolated native trees/ shrubs/ grass species in the above examples	Water impoundments; Urban and industrial landscapes; quarries and mines; Transport infrastructure; salt scalded areas

(Adapted from Thackway & Lesslie, 2006; Thackway & Lesslie, 2008).

We adapted the VAST-2 monitoring framework (Table 2) to further structure this review. VAST-2 is a hierarchical framework that captures the key stages of the degradation processes that affect any vegetation community modified by human activity. We have 'reversed engineered' this fundamental understanding of degradation processes to identify the key ecological functions, vegetation structures and biotic composition of grassy woodlands that must be re-instated over time for successful mine site rehabilitation of grassy woodlands.

Table 2. List of condition components, key functional, structural and composition criteria, and performance Indicators that must be suitably reinstated for successful rehabilitation.

Several of the criteria are modified from the VAST-2 framework (Thackway & Specht, 2015). The second column of this Table is used to organise this literature review.

Condition components[1]	Key functional, structural and composition criteria	Performance Indicators
Functional	1. Soil hydrology	Rainfall infiltration and soil water holding capacity
		Surface and subsurface flows
	2. Soil physical status	Effective rooting depth of the soil profile
		Bulk density of the soil through changes to soil structure or soil removal
	3. Soil nutrient status	Nutrient stress – rundown (deficiency) relative to reference soil fertility
		Nutrient stress – excess (toxicity) relative to reference soil fertility
	4. Soil biological status	Organisms responsible for maintaining soil porosity and nutrient recycling
		Surface organic matter, soil crusts
	5. Natural disturbance regime	Area /size of disturbance events - foot prints (e.g. flood, fire, cyclone)
		Interval between disturbance events
	6. Reproductive potential	Reproductive potential of overstorey structuring species
		Reproductive potential of understorey structuring species
Structural	7. Overstorey structure	Overstorey top height (mean) of the plant community
		Overstorey foliage projective cover (mean) of the plant community
		Overstorey structural diversity (i.e. a diversity of age classes) of the stand
	8. Understorey structure	Understorey top height (mean) of the plant community
		Understorey ground cover (mean) of the plant community
		Understorey structural diversity (i.e. a diversity of age classes) of the plant
Compositional	9. Overstorey composition	Densities of overstorey species functional groups
		Richness – the number of indigenous overstorey species relative to the number of exotic species
	10. Understorey composition	Densities of understorey species functional groups
		Richness – the number of indigenous understorey species relative to the number of exotic species

[1]Modified from the functional, structural, and compositional levels of organization observed in biological diversity described in Figure 1 (Noss, 1990).

We have organised our report by reviewing what is known about re-instating the 10 criteria shown in the second column of Table 2. Under each criterion, we describe the nature of these fundamental features of any vegetation system. Our literature review includes what is known about the *Unmodified* or reference state for each of these 10 criteria of grassy woodlands primarily in eastern Australia.

The application of the VAST-2 framework requires the identification of reference site conditions that are least disturbed to act as a comparative benchmark for assessing what needs to be re-instated by the rehabilitation process and to monitor and assess changes in conditions of the rehabilitation site through time. At the outset of rehabilitation; the degree of divergence between the reference soil landscape units and the waste rock emplacement is the degree of rehabilitation that is necessary to transition the ecosystem condition of the waste rock emplacement over time. It is worth noting that the same framework applies equally to assessing an *Unmodified* or a reference state plant community and a rehabilitation site.

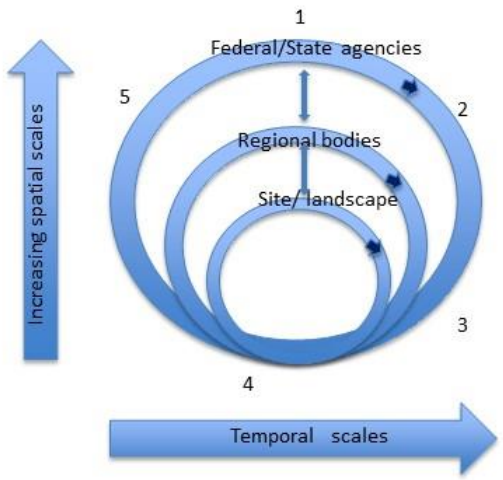
Both the reference sites(s) and rehabilitation site should be a spatially defined soil landscape unit, which is a relatively uniform area of geology, soil and topographic features and vegetation community (Thackway, 2014). It is essential to choose the same soil landscape unit for a reference site matched to the rehabilitation site (i.e. waste rock emplacement). The reference and rehabilitation sites should be on the same relative position on a catena or position in the landscape for appropriate comparisons to be made through time.

Elements of this framework used in this review include; knowledge of reference state ecosystems, ecosystem assembly rules and interactions between a physical growth medium (soil), plants and animals, disturbance regimes and environmental drivers including climate (Thackway & Specht, 2015). We assume that resilient ecosystems provide all of the required ecosystem functions without ongoing inputs including; nutrient cycling, pollination, substrate stability, and functional redundancy.

Critical to compiling a logical and comprehensive literature review for the rehabilitation of mined landscapes, an approach for describing, reporting and evaluating progress towards rehabilitation goals is needed (Tibbett, 2015). We adopted an iterative and stepwise process shown in Figure 1. This Figure corresponds broadly to phase 5 in the MRDC (Appendix 1) and to the state and transition model shown in Table 1. Figure 1 highlights the importance of space and time scales and using evidence-based learning from earlier steps to improve decision making in the following step. This figure also makes the point that using a state and transition model helps develop: rehabilitation goals, communicate aspirations, and monitor outputs and outcomes of rehabilitation.

Application of methodological framework

This literature review addresses Steps 1, 2 and 3 shown in Figure 1. Thus the first section of the literature review summarises the status of Box Gum Grassy Woodlands and defines goals for rehabilitation of this vegetation community. The second section of the review combines Steps 2 and 3 (Figure 1) to define the rehabilitation challenge and review leading practices (design solutions) for each of the key ecosystem criteria shown in Table 2. Steps 4 and 5 of Figure 1 (implementation of rehabilitation methodologies, and the evaluation of specific responses) are outside the scope of this review. These later two steps should be conducted on a site-by-site basis within the adaptive learning loops shown in Figure 1.



Steps or decision points for rehabilitating a Grassy Box Woodland community at multiple scales

Step 1: Define asset status and set goals - Describe the asset (plant community type/s) in terms of soil-landscape scales and the associated pre-European extent. Describe key historic local and regional events (who, what, when and where) that have changed asset's criteria and indicators of vegetation structure, composition and function, relative to a reference state (Table 2). Identify and describe goals and targets for rehabilitation using a state and transition model.
Step 2: Define the rehabilitation problem – For each criteria and indicator (Table 2) describe the extent and magnitude of change relative to a reference state.
Step 3: Design solutions – Investigate what are the leading practices used by rehabilitation practitioners and researchers to rehabilitate the criteria and indicators of structure, composition and function.
Step 4: Implement rehabilitation methodologies – Set priorities for investing in these leading rehabilitation practices. Implement a staged rehabilitation program with the aim to restore the framework criteria and indicators of structure, composition and function, relative to a reference state. Learn by doing using adaptive management, by adjusting practices to meet local circumstances and conditions.
Step 5: Evaluate the responses to establish trends- Monitor the spatial and temporal results of the rehabilitation to determine how well these outcome/s have meet the goals. Synthesise and report the outcomes using continuous measures for criteria and indicators of structure, composition and function and use a state and transition model to help with communicating aspirations, progress towards targets.

Repeat steps 1-5 as required.

Source: Modified from Fig 2 in (Thackway, et al., 2013), Fig. 1.1 from (Tongway & Ludwig, 2011) and Figure 2 in (Burger, 2015)

Figure 1. A five-step procedure for rehabilitating damaged landscapes. If assessed trends are not acceptable, this framework provides an adaptive learning loop to help achieve success by adjusting rehabilitation technologies and practices.

For each of the 10 rehabilitation criteria shown in Table 2, we highlight as exemplars, those scientific studies and industry reports, as well as leading practices, which effectively reinstate each of the 10 criteria. For each criterion we used a common set of headings:

- **Problem definition:** A brief description of the challenges in rehabilitating each criterion.
- **Ecosystem Criterion definition and attributes:** Each criterion is described and ways (attributes) to measure its condition (status) are summarised
- **Reference state conditions:** Attribute levels of each criterion are provided, if known, for least disturbed grassy woodlands
- **Design solutions and leading practices:** Effective ways to reinstate (rehabilitate) each criterion are reviewed. This is not an exhaustive review of practices as few are described in publically available documents.
- **Implementation risks**: Uncertainties in the effectiveness of design solutions and leading practices are described and triggers for post-implementation are suggested.
- **Knowledge gaps and priority research:** Priority research needed to address uncertainties in re-instating each ecosystem criterion is identified.

Complementary interviews and field inspections

There is considerable rehabilitation experience, expertise and field sites relevant to restoring grassy box woodlands. It was beyond the scope and resources of this review to conduct a comprehensive survey of restoration experts and restoration sites, but we did interview a sample of key researchers and practitioners. We conducted multiple interviews with Mr Owen Whittaker (Natural Capital Pty Ltd) including visiting some of his grassy woodland rehabilitation sites near Canberra. We also interviewed Donna and Andrew of DnA Environmental Pty Ltd including inspecting photographic records of locally occurring grassy box woodland rehabilitation of hard rock mining. In addition. R. Thackway attended the 2016 *Best Practice Ecological Rehabilitation of Mined Lands Conference* (Singleton, NSW) that including a field trip and numerous interviews. D. Freudenberger also conducted interviews with senior research staff at the Centre for Minded Land Rehabilitation (University of Queensland). Both report authors conducted field inspections of coal mine woodland rehabilitation and offset areas at four mines in the Boggabri district of NSW with Whitehaven Coal environmental staff.

Review Results

Step 1: Define asset status and set goals

Characteristics of least disturbed (intact) plant community

The natural distribution of Box Gum Grassy Box Woodland (*grassy woodlands* for brevity) extends along the western slopes and tablelands of the Great Dividing Range from southern Queensland through NSW and the ACT to central Victoria (Beadle, 1981). This community also extends into the Hunter valley. The pre-European extent of Grassy Box Woodland coincides with the distribution of relatively fertile soils (New South Wales Department of Environment, Climate Change and Water, 2010).

A key feature of grassy woodlands is the interaction between warm and cool season rainfall patterns and the effect this has on long term observed patterns of function, structure and composition including germination and recruitment events. It is likely that patterns of El Niño and La Niña, are the most important driver of year-to-year variability in climate of unmodified Box Gum Woodlands. The different phases of ENSO can cause droughts and floods. El Niño and La Niña events drive changes in circulation, winds and rainfall. Each El Niño and La Niña event is different and they have different ecological effects in space and time (Australian Government 2016).

Unmodified grassy woodlands (Table 1) are characterised by a species-rich understorey of native tussock grasses, herbs and scattered shrubs (where shrub cover comprises less than 30% cover) (New South Wales Department of Environment, Climate Change and Water, 2010). *Unmodified* remnants of this plant community are dominated or co-dominated by one or more of the following overstorey species (or hybrids of these species with any other *Eucalyptus* species): White Box (*Eucalyptus albens*), Yellow Box (*E. melliodora*) or Blakely's Red Gum *(E. blakelyi)* [or Western Grey Box *(E. microcarpa)* or Coastal Grey Box (*E. moluccana*) in the Nandewar bioregion] (New South Wales Department of Environment, Climate Change and Water, 2010). In the woodland state, tree cover is generally discontinuous and of medium height with canopies that are clearly separated.

Over the last 200 years the extent and condition this plant community has been extensively fragmented and modified (*Modified* and *Transformed*; Table 1) from a natural reference state by many land management practices including livestock grazing and by thinning and clearing of the overstorey. Many grassy woodlands have been converted from native vegetation to improved pasture and cropping (*Adventive* and *Replaced and managed;* Table 1).

These land use and land management practices have created a mosaic of condition states including woodland and derived native grassland. Today unmodified remnants (i.e. *Unmodified*; Table 1) are now highly restricted and exist as isolated and small patches (Thackway, 2010). Very few large and *Unmodified* remnants remain anywhere across its former range.

Many patches of *Modified* woodland and derived native grassland do still retain important components of this ecological community (e.g. depleted native ground cover composition, particularly robust perennial grasses and native soil biota). These *Modified* grassy woodlands also provide important habitat for fauna (isolated native trees with hollows, fallen timber, bush rocks and rocky outcrops) (Department of Environment, Climate Change and Water, NSW, 2010).

Where there has been a major disruption to these ecosystem functions, (e.g. agriculture, urban development or through open cut coal mining), these functions (e.g. seasonal ground cover, seed bank and soil biota) and/or habitat have essentially been disassembled (i.e. *Removed* Table 1). In reassembling these functional, structural and compositional components of grassy woodlands, it will be necessary to reconstruct these components during the rehabilitation phase and to allow time (in cases many years, decades and even centuries) before these components will have fully equilibrated to a dynamic stable state which approximates a *Transformed* or even a *Modified* grassy woodland community.

Steps 2 & 3: Define rehabilitation problem and design solutions

Functional criteria

The modified VAST-2 framework shown in Table 2 above identifies six fundamental ecosystem functions that must be re-instated during the early phases of the rehabilitation process of mined surfaces. These are: soil physical status, soil hydrology, soil nutrient status, soil biological status, the natural disturbance regime and the reproductive (regenerative) potential of the system. For each of these functional criteria, the criterion is defined, the rehabilitation challenge is described and key attribute levels found in the reference state are summarised (if known). Rehabilitation design solutions, leading practices and implementation risks are reviewed. Finally, knowledge gaps and priority research are suggested for reducing the uncertainty and risks of re-instating each of these functional criteria of effective rehabilitation.

Before commencing rehabilitation works it is critical to ensure that the key functional processes can be reinstated approximately matching those found in the natural reference state (Lawrence, et al., 2007). For this reason, an understanding of the ecological importance of the functional components is critical when considering reassembling plant communities. Once consideration is given to reinstating these functional processes, then the structure and composition components are integrated into the rehabilitation process. The rationale for this order is based on long established ecological theory and practice. As a general ecological principle, where human modification of the biotic component is slight, then the biotic components are liable to be unaffected (Hone, et al., 2015). Where the modification of the biotic components, that is the structure and composition, is large or total then there is liable to be little, slow, or no recovery of the biotic components and the abiotic components are liable to be obviously affected, both relatively to the biotic components and absolutely (Trudgill, 1988). Successful rehabilitation and recovery, in the case of large or total modification of function, structure and composition, will depend more upon the reserves inherent in the abiotic components and the way in which the biotic components act upon them to mobilize them (Trudgill, 1988).

1. Soil physical status

Ecosystem criterion definition and attributes

We define this criterion in its broadest sense including the depth and slopes on which soils are placed on mined surfaces. This criterion includes the physical and geo-chemical nature of the regolith which is the unconsolidated materials underlying the topsoil. The regolith of mined surfaces is often made up of over-burden materials of various ages and properties that affect plant survival and growth. Using the substrate definition of Speight and Isbell (2009) waste rock emplacements are 'stabilised soil' and described as artificial mass with a strength grade of very week rock.

The physical stability of soils re-instated on mined surfaces is included in this criterion. Physical stability refers to the capacity of the topsoil to remain in place rather than rapidly erode. Tongway and Ludwig (2011) provide a rapid method for assessing soil stability that integrates visual estimates of soil cover, litter cover, cryptogam cover, soil crust brokenness, erosion type and severity, deposited materials, surface cohesion and results from a slake test.

From a rehabilitation perspective, a key attribute of the topsoil and regolith is effective rooting depth. Roots, particularly eucalypt tree roots can penetrate a regolith of to a depth of 10 m or more depending on the availability of ground water at such depths (Stone and Kalisz, 1991) and degree of weathering. Though, the majority of roots of trees, shrubs and ground cover herbages utilize the top 50 cm of topsoil and regolith.

Problem definition

Rehabilitation of mined surfaces commences with the establishment of final landforms based on the emplacement of suitable overburden materials that is likely to form a functional regolith that allows root penetration, and remains stable when wet.

Waste rock emplacements are composed of particles of rock highly fragmented by the blasting/mining process with a size distributing from clay to size of large 4WD. The primary porosity of waste rock emplacement contain an estimated 30% void space which must be conducive to root penetration and growth if the isolated/heterogeneous distribution of compaction surfaces (again is only shallow <0.5m) can be overcome. The shaping of waste rock emplacements usually results in some compaction of parts of the final land surface which can severely limit the effective rooting depth of the soil profile and can change the bulk density of the soil.

The shape and slopes of mined surfaces is likely to influence rehabilitation processes and trajectories for centuries if not millennia. Topsoil must then be placed on the final land forms in such a manner as to remain stable and resistant to rapid erosion, at the same time being conducive to plant growth.

Reference state conditions

The shape and slopes of grassy woodlands in a reference state have been shaped by millions of years of landscape evolution. This includes a great deal of fine scale heterogeneity of soil properties. In general, shallow, course textured and highly leached soils are found at the top of slopes. Deeper, fine textured and more fertile soils are found on lower slopes and plains (Figure 7 Criterion 9). This fine scale heterogeneity in soil properties drives the fine scale species diversity of the local flora (Figure 7). An example of this fine scale heterogeneity of soil properties for a grassy woodland in a reasonable reference state is found in McIntyre et al. (2010). In references sites, care needs to be taken not to reduce the soil physical status of these sites. Some key factors include limiting total grazing pressure at critical periods exposing bare soil to run-off; avoid physical disturbance and compaction of the topsoil (refer to Appendix 2).

Design solutions and leading practices

Under typical Australian legislation regulating mining operations mine site rehabilitation must establish “a safe and stable environment”. This task starts with designing and establishing the final landform. Traditionally this has been shaping to a final slope of a maximum of 10^{o} with linear batters and berms. Complex landform designs have been developed using the GeoFluv landform design software, with designs based on a range of observed landform parameters. The GeoFluv approach is predicated on the proposition that stable, natural landforms used to derive its input parameters will have erosion characteristics identical to those of the mine wastes used in landform construction. Loch (2010) found that the crucial assumption within GeoFluv can be difficult to satisfy for the relatively ancient landscapes such as in Australia, where soils are strongly differentiated in terms of both landscape position and depth in the soil profile. In addition, topsoils placed on constructed landforms may have significantly higher erodibility than assumed in GeoFluv. Consequently, Loch (2010) found that the GeoFluv approach generated landforms with the highest erosion potential. However, using various modelling tools, Loch (2010) found that “although all landform designs varied in their estimated erosion potential, they were all shown to be stable if well vegetated, demonstrating that soil management to maximise vegetation establishment and growth is a crucial component of landform rehabilitation in this area [Hunter]”.

The next step in the earliest phases of mine rehabilitation is the selection and placement of appropriate waste rock (spoil) covers if unsuitable or adverse waste rock is thought to be an issue. Henderson (2008), provides detailed specifications for suitable spoil covers. These specifications are primarily related to minimising flow water through problem spoils, hence will be summarised under the next criterion – Soil hydrology. However, the author also provides physical specifications of suitable spoil covers as follows (Henderson 2008, p.3):

“Particle size distribution was identified as the most important inherent property affecting cover performance, but because of the influence of construction/handling methods, only broad limits were inferred, namely:

- Too much clay/silt would cause too much runoff and consequent erosion;
- A coarse spoil with little or no clay would allow too much infiltration for its retention capacity;
- The spoil should be well graded (that is, have a smooth concave particle size distribution curve); and
- There should be more gravel and cobbles (>2mm) than sand”

We acknowledge that the process of coal mine rehabilitation, little consideration is given to the issue of spoil characteristics unless there is known to be carbonaceous or acid generating spoils; then those are buried away from the final landform surface (Andrew Wright pers comm).

This research also provides a simple wetting and drying test of pre-mining geological cores to inexpensively identify suitable overburden covers.

As the spoil cover will become the regolith of vegetated slopes, material compaction preventing root penetration must be minimised. Lessons from bauxite mining are presented here however, we note there are inherent differences between open cut coal mining and bauxite mining. In bauxite mining the rehabilitation surface is basically the floor of previous mining pit because there is very little overburden and therefore is heavily compacted by machinery operating on top of but also because it is the *insitu* bed rock below the bauxite. For this reason, pre-ripping should occur between the final land forming and topsoil return stages of the rehabilitation process (ALCOA Australia, n.d.). ALCOA in western Australia jarrah forests now routinely practices pre-ripping in all pits and to ensure that 80% of the pit (excluding batters and waste islands) is pre-ripped to a depth of between 1.2 - 1.5 m or greater in order to promote vegetation establishment and growth (Grant & Koch, 2007). A real-time monitoring system located in the cab of the dozer is used to monitor the area that has been ripped and the depth of ripping. This monitoring system provides guidance and enables the dozer operator to meet target for the pit and identifies areas where rework is required prior to shifting to another location (ALCOA Australia, n.d.).

In contrast to bauxite mining, coal mining has significant quantities of overburden; thus the waste rock is used to backfill the mining void. Other restoration scientists and practitioners also recommend reducing compaction to minimise erosion and sedimentation by ripping and the use of spiked rollers to aerate soils to depth of 30 cm (Rawlings, et al., 2010); (Whitaker, 2016) (Tongway & Ludwig, 2011).

The dispersive properties of the salvaged soils are now routinely identified during the process of replacing the overburden on the final land surface of rehabilitated sites by adding soil ameliorants to reduce the sodicity and therefore dispersivity (Tongway & Ludwig, 2011). Experience of rehabilitation practitioners also recommends that topsoil separately stockpiled for later use to cover newly constructed landscapes. This process, known as capping, positions the more dispersive spoil materials, such as high sodicity and high pyritic (acid sulphate) concentrations, deeper in the reconstructed final landform, where they are less likely to cause problems, such as tunnelling (Tongway & Ludwig, 2011).

Where compaction of the regolith is considered an issue and potential limitation, the area should be deep ripped. Following deep ripping of spoil covers created from appropriate waste materials, topsoil should be placed to depths as great as the available soil resources allow. We note that there is no standard depth to replace the topsoil, rather reconstructed soil depth is a function of the soil balance (area x depth of soil stripped vs area x depth of rehab to be soiled) (Andrew Wright pers comm). Where possible, to mimic natural soil profiles found in woodlands, a minimum of 200 mm of quality topsoil should be placed with minimal compaction. The issues and best practice of ensuring quality topsoil is reviewed below under the criterion 'Soil Biological Status'.

During the critical germination, establishment and development phases of rehabilitation, it is important to understand the soil physical status. Numerous factors can affect the likelihood of success in rehabilitation including: shaping the final land form to promote landscape evolution and succession over time; roughing up the soil surface to promote germination; controlling total grazing pressure to prevent soil compaction; using soil ameliorants as required to improve the structure of topsoil to prevent water erosion; establishing a ground cover as soon as possible to bind the soil from overland water flows; using organic and inorganic mulches to prevent the soil from slaking and sourcing high quality seed mixes. It is widely acknowledged in the sequence of rehabilitation that functional criteria, in particular the shaping the final land form to promote landscape evolution and establishing a successional ecosystem pathway is fundamental; before initiating rehabilitation of criteria of composition and structure (Walker, et al., 2007; Tibbett 2015).

Establishing an appropriate environment for vegetation establishment, particularly from seed, involves making sure that the topsoil has some surface roughness (Whitaker, 2016). Owen Whittaker is representative of grassy woodland rehabilitation practitioners that uses tractor-pulled machinery which roughen the ground after a grader or bull dozer has distributed the top soil. Roughened surfaces enable grass and forb seeds to fall or wash into appropriate microsites for germination. This can also be created using a set of harrows pulled behind the direct seeding implement.

On steep slopes a mounding plough (Figure 2) may also be used to create furrows and mounds across the slope to limit the risk of soil erosion caused by overland flow and to enable surface flow to percolate into the substrate / waste rock emplacement.

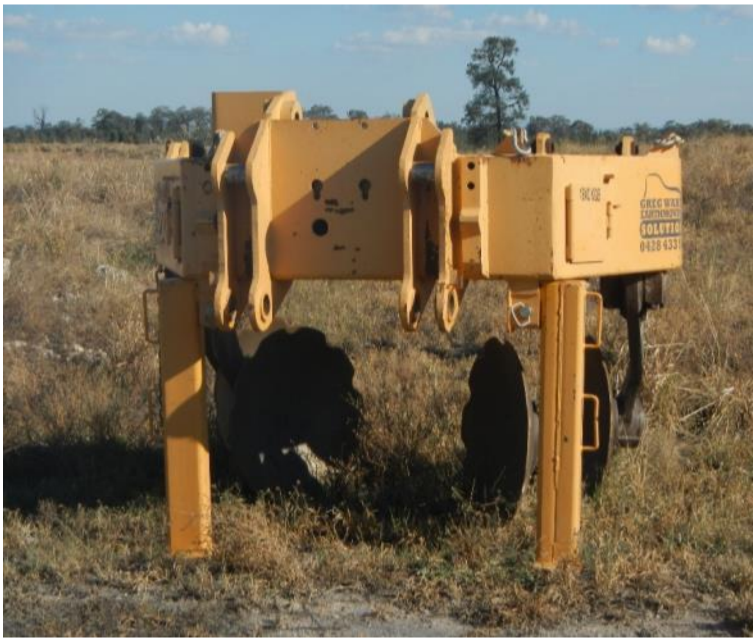


Figure 2. Mounding plough may also be used to create furrows and mounds

Implementation risks

Use of highly dispersive overburden capping materials and dispersive topsoils increases the risk of accelerated rates of erosion, gully formation as discussed in more detail in the next section. The authors during a field visit to the Gunnedah coal mine region were appraised of this issue regarding the dispersivity and slaking properties associated with the final landform and the topsoil from weathered sandstone derived from ancient marine deposits. During these field inspections topsoil and regolith compaction did not appear to be a problem, but has been witnessed on rehabilitated slopes in the Upper Hunter leading to poor tree growth.

Knowledge gaps and priority research

We could not find any research papers or industry reports on how the root systems of grassy woodland vegetation utilises the constructed (novel) regoliths created during the final land forming phase of rehabilitation. However, we were informed that Boggabri Coal Pty Ltd has commissioned an investigation into this subject, but the final report was not available at the time. We recommend that this report be made publically available as it may be the first of its kind. We hypothesise that the issue of root penetration of overburden capping materials is an important research topic. Long lived trees (centuries) do not utilise just 200 mm of topsoil but rather must access the regolith to unknown depths to anchor themselves upright and access water and nutrients at depth. It is hypothesised that deep ripping of capping materials facilitates root access to the regolith, but this has not been demonstrated experimentally. It is also hypothesised that certain woodland tree species can utilise constructed regoliths and their roots may help reduce the risk of sub-soil erosion (e.g. tunnelling). For example, it appeared that ironbark trees growing on the upper slopes being cleared for mining were perhaps 50-100 years, had very shallow roots (Figure 3). The site was stable on natural regolith despite shallow roots. The same is likely to be true when in this part of the catena when the final landform is rehabilitated with the same ironbark trees species.

Figure 3. There was little evidence of deep rooting of native eucalypts growing on the upper slopes of a mine site in the Gunnedah region

Mounding appeared to be practiced on some coal mines in the Gunnedah region and not others. We also noticed variation in spacing between mounds. Research trials are warranted to investigate the value of mounding compared to just ripping. Trials should also be conducted on the rehabilitation (functional) value of spacing between mounds. The longevity of these mounds should be monitored as well.

Anecdotal practice of one mine in ameliorating some of their soils and regoliths shows that it is necessary and beneficial to 'double gypsum' to reduce the site's dispersive soil properties. This involved a two stage process; first gypsum is applied to the reshaped final landform after it is ripped and before the topsoil is overlain; and second, additional gypsum is mixed with the topsoil and mulch prior to it being spread over the final landform. The costs and benefits of such soil and regolith treatment with gypsum requires further investigation.

2. Soil hydrological status

Ecosystem Criterion definition and attributes

The capacity for soils to capture and store rainfall is a fundamental criterion of any vegetated ecosystem. The capture of rainfall by water infiltration is a complex process affected by physical and biological status of a soil (Tongway and Ludwig, 2011). The opposite of infiltration is surface water runoff. Water infiltration can be measured directly with a rainfall simulator or disc permeameter (Eldridge and Freudenberger 2005), or measured as an index that is made up of visual estimates of perennial plant cover, litter origin and composition, soil surface roughness, surface coherence and the slake test (Tongway and Ludwig 2011).

The capacity of a soil to store water includes plant available water capacity (PAWC) that comprises three measures (Burk & Dalgliesh, 2008):

- Drained upper limit or field capacity – the amount of water a soil can hold against gravity
- Vegetation Type Lower Limit – the amount of water remaining after a particular vegetation type has extracted all the water available to it from the soil
- Bulk density – the density of the soil, required to convert measurements of gravimetric water content to volumetric

PAWC may be altered through a range of management practices, which may alter the ability of the soil to absorb water (for example through surface sealing), or reduce the capacity of the soil to hold water (e.g. by compacting the soil or through physical removal of soil material) (Thackway, 2014). PAWC may be increased in certain circumstances (e.g. through the addition of organic matter, or physical alteration of the soil structure or texture, as in addition of clay to sandy soils or gypsum to clayey soil). Alteration of PAWC may be long-term, or relatively short and requiring ongoing management inputs (Thackway, 2014).

Problem definition

The rapid establishment of vegetative cover is necessary sustain a biologically healthy and stable topsoil which is critical for protecting the often erodible substrate (overburden capping) from exposure to rain droplet erosion, rill and gully erosion, and tunnelling caused by surface or overland flows and subsurface flows (Burger, 2015). A dysfunctional soil surface with little vegetative cover sheds water (low infiltration) and has poor water holding capacity. The rapid establishment and development of a perennial vegetative cover plays a critical role in enhancing water infiltration, reducing run off (erosion) and maintaining or improving plant available water holding capacity (Tongway and Ludwig 2011).

Reference state

Naturally developed landforms i.e. unmodified soils, are stable under current climate conditions showing little evidence of mass movement of the regolith and of soil erosion. Vegetation plays a critical role in stabilising landforms and soils and in the development of soil. Rainfall is effectively infiltrated into the soil and unmodified soils are able to hold soil water that is then available for plant communities i.e. soil water holding capacity. Naturally functioning landforms also intercept rainfall which is used by plant communities via surface or overland flow and subsurface flows or ground water. This process of highly efficient capture and utilisation of rainfall in a reference grassy woodland has been documented by Eldridge and Freudenberger (2005). They found that under mature eucalypts steady state water infiltration averaged nearly 150 mm/hr on fine textured soils, whereas on the same soil, but cultivated, infiltration was around 10 mm/hr. Under native perennial grasses, water infiltration was around 25 mm/hr.

Design solutions and leading practices

In Australia, it has been common practice for regulatory agencies to specify batter angles and flow networks (e.g. level or graded banks and rock drains) that have been widely applied when reshaping waste rock emplacements into post-mining landforms, creating safe, stable, non-polluting landscapes and able to sustain an agreed post-mining land use with self-sustaining vegetation (Howard, et al., 2011). Such shaped rehabilitated waste rock emplacements tended to result in rills and gullying due to combination of factors including landform shape, soil erosivity and surficial soil conservation banks and structures which inappropriately concentrated surface flows.

Successful rehabilitation of soil hydrological properties is closely related to reshaping of the landform post-mining (Spain, et al., 2015). The process of reshaping the final waste rock emplacements, including regolith, into landforms that are found outside the mined area has essentially been the domain of mine engineers, although it has obvious ecological relevance as well. Over time there has been a willingness on behalf of mining companies to embrace reshaping of waste rock emplacements materials so that the final landform patterns and elements blend into the surrounding landscape.

After the final landform has been shaped, finer scale earth works are undertaken to minimise erosion including the treatment of dispersive soils and spoils, design and implementation of batter slopes, the use of structural erosion controls (e.g. channel banks, slope drains and energy dissipaters) and the use of benign (hard rock) mulch to stabilise batter surfaces to provide stable land surfaces (Wright, 2016).

In recent years advances in computers and their software have led to the development and application of post-mining final landform simulations based on a number of inputs including, climate records, geology, terrain and soil characteristics (Howard, et al., 2011). The resulting models show relatively 'natural' and complex reshaped landforms designed to reduce their erosion potential.

A major benefit of these three-dimensional landform models is that they can be downloaded into GPS enabled equipment for final landform shaping by skilled operators. In addition, some of the landform models are dynamic and provide insights into what the landform might look like long into the future as a result of landscape evolution driven by weathering and erosion (Howard, et al., 2011).

Such landform models have been used by Mangoola Coal, Wybong to successfully develop complex natural landforms in reshaped mine overburden (Willis, 2014). Monitoring over time of the final landform showed it was stable, was visually sympathetic with the surrounding environment. After the landform was shaped, areas are strategically targeted for specific vegetation types that occur in the surrounding local area, based on similar topography, slope, aspect and topsoil type (Willis, 2014).

Establishing a vegetative or non-vegetation cover as soon as practicable following topsoil placement is recommended (Rawlings, et al., 2010); (Johnston, 2008). Rock mulches have proven effective for stabilising dispersive topsoils (Smits 2008), but stable rock may not be available from coal mine operations since the overburden is often composed of relatively unstable tertiary marine deposits. Sowing of a short-lived exotic (non-native) sterile cover crop to reduce erosion risk and build fresh soil carbon has proven useful and is generally practiced to rapidly stabilise recently placed topsoils. Sowing of winter active, or summer active, or both ought to be considered, but the advantages of either crop types or combinations requires further investigation.

Establishment of a native grass cover crop established by sourcing and applying native hays with viable seed or directly sowing native grass seed should also be considered (Whitaker, 2016); (Johnston, 2008). Huxtable (1999) identified five species of native grass suitable for rehabilitation of mined surfaces in the Hunter Valley. Huxtable (1999) and practitioners like Whitaker (2016) have identified or developed machinery for native grass seed harvesting and sowing, but sourcing native grass seed remains a relatively expensive challenge due to a highly variable supply and quality.

Research in the Hunter Valley found that quality topsoil relatively free of exotic weed seed was critical for the successful establishment of native grasses covers (Huxtable 1999). If the weed seed bank in the topsoil was high, completion from weeds out-competed native grasses over a period of 4.5 years.

Implementation risks
Care needs to be taken to minimize the impacts of uncontrolled overland flows during critical periods: germination, establishment and development phases. In rehabilitation sites, avoid off-site run-off and seepage from waste rock emplacements which may contain contaminants (refer to Appendix 2).

Knowledge gaps and priority research
Studies of the soil water-holding capacity of stored topsoil compared to an undisturbed reference state, showed significantly less available soil water-holding capacity in the reinstated topsoil of rehabilitated final landforms for 1.5 to 2.5 years after rehabilitation commenced, being only 65% of that observed in an undisturbed reference state site (Harris & Birch, 1989). It is unclear whether this difference would be same for topsoils that are reinstated and used for the rehabilitation of Grassy Box Woodlands.

It is widely recognised by restoration ecologist, practitioners and the industry that rapidly establishing a 'cover-crop' on newly spread topsoil on final landforms is critical to stabilise soil surfaces, improve water infiltration (discussed in the next section) and improve biological activity of the soil. Traditionally cover-crops have been established by sowing summer active or winter active non-native cereals (e.g. millet or rye corn) for which seed is readily available, inexpensive and sowing technologies are well developed. Use of such non-native covers is appropriate if the final land use is grazing of introduced pastures, but may not be the most effective strategy for restoring grassy woodlands. Research is needed to investigate how these traditional cover crops negatively or positively affect the establishment of native grassy ground covers. Alternative organic covers should also be investigated such as native hays or rice straw that is very low in terrestrial weed seeds and has been shown to effectively 'stick' on recently placed topsoils (Whittaker 2016). Examples of Owen Whittaker's rehabilitation practices are shown in Figure 4 (a-f).

3. Soil nutrient status

Ecosystem criterion and attributes
The nutrient status of soils influences the establishment and growth of both native and non-native (e.g. weed) species. Grassy woodland species have generally evolved under low soil nutrients, particularly Phosphorus, but many will respond to higher levels of soil fertility. However many non-native ground cover species also respond to higher levels of fertility and can effectively outcompete native species (Huxtable 1999). Standard methods for soil sampling and measurement of soil nutrients is provided by McDonald and Isbell (2009). Soil nutrients include, N, P, K, S as well as other various minerals and trace elements. Measurement and monitoring of pH is important as it affects nutrient availability. Salinity (e.g. electrical conductivity) should also be monitored as salts at high concentrations negatively affect most grassy woodland plant species.

For example, the following soil nutritional attributes were collected and analysed for reference and rehabilitation sites at the Mount Thorley Warkworth and Hunter Valley Operation:

- pH - a measurement of the acidity or alkalinity of a soil. Excessive acidity or alkalinity will interfere with uptake of nutrients by plants. pH is a measure of the acidity and alkalinity of the soil using a scale from 1 to 14; where 7 is neutral, less than 7 is acid and greater than 7 is alkaline.
- Sodicity - the amount of sodium held in a soil. Sodium is a cation (positive ion) that is held loosely on clay particles in soil. It is one of many types of cations that are bound to clay particles. Other types bound to clay particles include calcium, magnesium, potassium and hydrogen.
- Electrical conductivity (EC) - a measurement that correlates with soil properties that affect vegetation productivity, including soil texture, cation exchange capacity (CEC), drainage conditions, organic matter level, salinity, and subsoil characteristics
- Electrochemical Stability Index (ESI) - an index used to express the relationship between sodicity and salinity.

a) b)

c) d)

e) f)

Figure 4. Illustration of the steps used to rehabilitate exposed rough regolith in the Canberra region.

Fig 4. a) rough ripped former dirt road comprising a rough surface of large clay clods aggregated gravel and small rocks, b) rice straw is blown onto the land surface to a depth of about 3-5 cm thick, c) water sourced locally is pumped into the tank of the hydro-seeder, which provides the dispersive agent into which large quantities of locally indigenous grass and herb seed is loaded and mixed, d) water and seed are continuously mixed in the hydro-mulcher and sprayed onto the rice straw. NB: No additives are mixed to help the seed stick to the mulch, e) and f) examples of a rehabilitated road prepared and seeded using steps a) to d). NB: no irrigation was applied to the site while it is germinating, establishing and developing. Trees and shrubs were hand-planted and protected with tree guards to prevent browsing by rabbits and kangaroos.

- Plant available nutrients - The macronutrients (nitrogen, phosphorus, potassium, sulphur, calcium and magnesium) are required in relatively large quantities by plants. Plant growth may be retarded because: these nutrients are lacking in the soil or they become available too slowly.
- Cation balance - is a calculated value that is an estimate of the soils ability to attract, retain, and exchange cation elements. Soils with a high cation exchange capacity have a high clay context, have a greater capacity to hold nutrients in a given soil depth, have a higher water holding capacity. The converse applies to soils with a low cation exchange capacity. The capacity of a soil to hold the major cations Ca, Mg, Na, and K (and in very acid soils hydrogen (H), aluminium (Al), and Mn) in this way is referred to as the Cation Exchange Capacity (CEC). It gives a measure of the general fertility of the soil, and is important because cations held on the exchange complex are protected from being leached out of the root zone.

The method used in the Mount Thorley Warkworth and Hunter Valley Operation (Niche Environment and Heritage, 2016) involved a composite sample consisting of sub-samples collected 10 to 15 m apart, collected within a 20 m radius of the site's centre. The radius is based on a central point five metres in from the 20 metre quadrat tape. All samples were placed in a bucket, and were mixed. The sample is then placed in a plastic bag, labelled and sent to a laboratory for analysis and interpretation. Subsequent monitoring uses the same procedure.

Problem definition

Australian soils have inherently low levels of soil fertility. The process of mining can reduce even further these levels. It is therefore critical to know the source of topsoil used in rehabilitation because under intensive agricultural land management the addition of exogenous fertilizers (N, P, K) and trace elements used to promote pasture growth and crop production can create hostile soil conditions for rehabilitating and restoring many of woodland species, especially native forbs.

Higher nitrate levels in degraded remnants rarely grazed reference sites were observed by (Prober, et al., 2002). Degraded remnants correspond to the *Transformed* class (Table 1). Results of soil analyses showed the physical and chemical properties of the topsoil were a major determinant of understorey composition within such remnants. Degraded remnants were relatively low in soil nutrients, more acidic and more compacted (bulk density) than ungrazed remnants, and that high soil nitrate levels favour the dominance of annual and biennial weeds including Rye Grass (*Lolium rigidum*), Black Oats (*Avena barbata*) and Paterson's Curse (*Echium plantagineum*). The effect of the soil nitrate difference was associated with increased weed invasion, with exotic annuals replacing perennial natives, e.g. Kangaroo Grass. Temporary reductions in soil nitrate levels were achieved by the addition of carbon sources (such as sugar or sawdust), effectively limiting weed growth and favouring the establishment and growth of native ground layer species (Prober, et al., 2005) (Smallbone, et al., 2007).

Thus, soils used in rehabilitation that have been sourced from land that has been previously managed for improved pastures and cereal crop, hence fertility enriched, pose a serious threat to establishment of a diverse grassy woodland flora that is relatively weed free (Cole et al., 2006).

Reference state

Little disturbed (i.e. *Unmodified* Table 1) Box-Gum Grassy Woodland soils are naturally low levels of the macronutrients: NPK (Prober, et al., 2002). Within *Unmodified* remnants, at a local scale, soils under mature trees are more fertile and support a greater richness of understorey species than open areas. They also found that while Kangaroo Grass dominates open areas, Snow Grass tends to dominate under trees, and the abundance of both grasses is generally lower under trees facilitating the establishment of subsidiary species. Data on soil nutrient status in *Modified* grassy woodlands is also shown in Eldridge and Freudenberger (2005) and McIntyre et al. (2010). They also found spatially variable (patchy) concentration of nutrients depending on surrounding vegetation and history of land use. Organic carbon was particularly high (up to 7.5%) under eucalypt trees falling to about 2.5 % under grasses away from trees and just 1% carbon from a nearby long-cultivated field (Eldridge and Freudenberger 2005).

Design solutions and leading practices

Topsoil stripped from mined areas that were covered by native woodlands and forests should be carefully managed and conserved. They are likely to be naturally low in nutrients and have fewer weeds in the soil seed bank. Stockpiling should be avoided whenever possible. If unavoidable, these 'native' topsoils should be stockpiled well away from sources of weeds that often come from agricultural areas. Vehicle hygiene should also be high to avoid contamination of native topsoils from machinery carrying in weed seed. A cover crop for stockpiles of native soil, if shown to be necessary should be native grasses rather than exotic annuals. We noted at one coal mine in the Gunnedah region that a dense cover of acacias appeared to naturally form on stockpiled soils stripped from former areas of native vegetation (Figure 5). Topsoil stripped from agricultural land uses should not be mixed with 'native soil' nor stockpiled near native soil.

Figure 5. A stockpile of soil stripped from mined areas that were dry forests that now has a cover of native vegetation that naturally regenerated from the soil seed bank.

At time of planting, fertiliser should only be used at each planted seedling or in each row of direct seeding if research trials have demonstrated that a benefit in seedling establishment and survival. Research in the Western Australian wheatbelt has shown improved establishment and survival rates incorporated at the time of direct seeding, but this type of direct seeding requires that narrow strips of the agricultural topsoil are removed (scalped) to reduce weed competition (Woodall 2010). Scalping is generally not necessary in mine rehabilitation. Broad scale fertiliser application should not be applied if the goal is the establishment of a grassy woodland. Native ground covers can generally tolerate quite low soil nutrient status.

Where topsoil has been stripped from areas that were formally mixed improved pasture and native grasses i.e. *Adventive* (Table 1) the soil is highly likely to contain a weed seed bank that is reactivated during rehabilitation. Following the first rains on the respread topsoil, broadleaf weeds typically germinate ahead of any native grasses and will rapidly expand to smother the slower growing native grasses. Where this is expected sowing a cover crop of oats plus a native summer active perennial grass (e.g. *Chloris truncate*), may be an appropriate initial strategy (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008). Some large native grasses, e.g. *Themeda australis*, Snow Grass (*Poa sieberiana*) and potentially Tussock Grass (*P. labillardierei*), can uptake significant quantities of soil nutrients and may be useful species when nutrient enriched topsoils must be used for the rehabilitating grassy woodlands (Prober, et al., 2002).

If topsoils are shown to be highly dispersive due to sodic properties, application of gypsum may be warranted. If pH is low, addition of lime should only be considered if field trials show that it improves the establishment of native species. It many cases, native species can establishment and survive on acid soils, since they have evolved with them.

Implementation risks

From our observations and review of the literature, the most significant risk is having to use topsoils that have been enriched by decades of agricultural inputs. Highly nutrient enriched topsoils are highly likely to have a large weed soil seed bank and these weeds can outcompete even rapidly growing native grasses as shown by Huxtable (1999) in the Hunter Valley.

Knowledge gaps and priority research

Field trials of tightly targeted application of fertiliser to enhance seedling establishment and survival should be conducted if poor seedling survival is shown to be a significant risk and if lab analysis shows low soil nutrient status well below reference levels.

If agricultural soils have to be used for grassy woodland rehabilitation, trials should be conducted to see if excess nutrients can by stripped from such soils by the repeated sowing and harvesting of crops with high nutrient uptake potential to mine/lower overall soil nutrient levels.

Replicated field trials testing the value of adding gypsum to sodic soils is probably not warranted. The value of gypsum for such soils is now well established and is likely to improve the establishment of grassy woodland vegetation rather than pose a risk.

4. Soil biological status

Ecological criterion definition and attributes

The biological activity of the soil promotes water infiltration, is essential for nutrient cycling including nitrogen fixation, and is fundamental to plant establishment, growth and survival. Soil organic matter is the primary source of energy that drives biological activity in the soil. Organic (living) soil crusts are also a key feature of soil life as crusts enhance soil surface stability; provide microsites for germination and some species can fix nitrogen within the soil crust. The soil seed bank is also a feature of the biological status of soil.

Soil biological status can be indirectly assessed by the index of nutrient cycling, a component of the soil surface assessment methodology describe in Tongway and Ludwig (2011). This index is based on observations of perennial plant cover, litter origin and decomposition, cryptogam cover, and soil surface roughness. The biological status of the soil can also be gauged by measurement of soil organic matter using standard laboratory analysis, or directly measured using a range of techniques including measure of soil respiration (Tongway and Ludwig, 2011).

Problem definition

Practices which remove, destroy or degrade indigenous surface organic matter, soil organic carbon pools, and disturb soil crusts include: mining, burning, grazing, stock trampling and cultivation. In the case of mining, significant soil disturbance is inevitable as topsoils are stripped. Even if immediately emplaced onto final landforms, losses of biological activity will occur (Jasper, et al., 1989). However, stockpiling topsoil causes the most significant impact biological activity as described below.

Research looking at the viability of vesicular-arbuscular mycorrhizal propagules in a four-year-old topsoil stockpile at depths greater than 1 m below the surface showed there were no viable propagules (Harris & Hirch , 1987).

Studies were made of the changes in microbial community of topsoils stockpiled during opencut mining in the United Kingdom (Harris, et al., 1989). Results showed that the numbers of aerobic bacteria decreased with increasing depth. The authors concluded that in the deepest parts of the older topsoil stores had only one-tenth the number of bacteria that were in either the upper parts of the stockpile or the undisturbed or reference topsoil. They also found that the deepest part of the topsoil mounds contained only 19% of the average total numbers of bacteria down the profile after 48 months of topsoil stockpiling.

Similarly for fungal spores, the deepest part of the oldest topsoil had less than one-thirtieth of the numbers that were found in the top part of the mound, and two orders of magnitude fewer than the undisturbed reference topsoil. The authors concluded that this major decrease may have been due to mechanical damage of the fungi’s filamentous growth habit caused by compression during stockpiling (Harris, et al., 1989).

Studies were also made of the viability of seeds, which showed topsoil stockpiled more than a meter deep, resulted in a decrease in viability of seeds (Harris et al. 1989).

Following this research three zones of microbial activity were proposed aerobic, transition and anaerobic (Harris, et al., 1989). The zones had the following characteristics:

“Aerobic Zone

- Flush of bacteria after construction.
- More anaerobes and spores than controls.
- Larger ammonium concentration than the control site.
- Microbial biomass less than control initially, but may recover to undisturbed values.
- Many previously dormant seeds may germinate and dominate the soil store flora, unless controlled chemically.
- The size of this zone probably depends on soil moisture status.

Transition Zone

- Fluctuates between predominantly aerobic and anaerobic states.
- May accumulate nitrate.
- Decline in biomass similar to aerobic zone.
- The size of this zone probably depends on soil moisture status.

Anaerobic Zone

- Bacterial groups are most affected in this zone.
- Larger percentage of the population as spores and anaerobes.
- Organic matter becomes more labile as a result of storage.
- Fewest fungal spores and least total microbial biomass.
- Little microbial activity when respread.
- Weed seeds persist for at least four years in this zone.
- Iron, manganese and copper appear in the available fraction, especially with increasing age.
- Plants grown on the soil from this zone initially grow well.
- Size of this zone may depend on a combination of soil texture and moisture status.

Drier stockpiles had greater infection rates indicating greater survival; the high moisture may allow spores to germinate, where they would not survive due to lack of host. Increased survival under lower water availability may reduce activity of mycorrhizal fungi and spore germination (Miller, et al., 1985).

Decreases in microbial activity in top layers of stockpiled soils, measured by respiration rates, where found within 15 days of laying down the stockpiles. Loss of organic carbon was attributed to exposure to temperature extremes and desiccation (Visser, et al., 1984).

Similar stockpile research has been conducted on three coal mines in the Hunter Valley (Keipert et al., 2004). They examined a wide range of soil parameters across three stockpile heights (2, 4 and 6 m) and ages (0, 6, 12, 18 and 30 months). During initial stockpile construction, many soil parameters (e.g. microbial respiration, total N and soil organic carbon) decreased by up to 50%, indicating that deterioration of soil quality is rapid and initially independent of stockpiling. Within each site, age of stockpiles was the most significant factor affecting soil parameters. For example, microbial respiration decreased over time. The 2 m stockpiles had greater levels of soil organic carbon and nitrate-N indicating maintenance of soil quality, while ammonium-N was greater in the 6 m stockpile due to ammonification occurring under anaerobic conditions. Nitrate-N, ammonium-N, electrical conductivity, available P and some exchangeable cations increased with depth as a result of leaching, although an accumulation at the base of the taller stockpiles meant that nutrients were not lost completely. Deterioration of soil quality during stockpiling was greater for the clay loam soils compared to the loam and sandy loam soils. The authors concluded that stockpiling topsoil under the relatively dry conditions experienced during this study had a relatively minor impact on soil quality, particularly when compared to the initially large impact of handling topsoil with heavy machinery.

This research (Keipert et al., 2004) then examined the outcomes of spreading the stockpiles onto rehabilitation areas. They found that height of stockpiles had little influence on soil quality in the rehabilitation areas, suggesting those parameters that did deteriorate as stockpile height increased can be rectified by soil mixing and oxidation during the respreading process. Still, the authors recommend that "topsoil should be directly returned, whenever possible, to areas that are being rehabilitated rather than stockpiled".

Where stockpiling is unavoidable, this report recommended the following where practicable:

"Stockpile Construction

• Soil can be stored in stockpiles greater than 3 m in height depending on the period of storage, the predominant soil type at the mine site and the level of amelioration undertaken in the rehabilitation process. These recommendations only relate to mine sites in the Hunter Valley rehabilitating land to a pasture final land-use and should not be extrapolated to areas elsewhere in Australia where the rehabilitation objective is to return diverse native ecosystems.

• Mine sites that have soils with higher clay content should store topsoil in lower stockpiles for shorter periods of time than sites with sandier soils. Alternatively, these sites can store clay soils in taller stockpiles on the provision that they can increase the level of amelioration of rehabilitated areas that receive this stockpiled topsoil.

• The geometry of stockpile construction is important and it is better to create free-draining stockpiles to prevent anaerobic zones forming rather than trying to maintain nutrients at the base of the stockpile. Therefore, stockpiles should continue to be shaped to prevent erosion but encourage water runoff, without the loss of soil.

• Maintain seeding of stockpiles to reduce erosion and the loss of beneficial soil microorganisms by rapidly establishing vegetation cover. The seed mix should contain deep-rooted species (e.g. Lucerne), nitrogen-fixing species (e.g. clovers and medics) and grasses (e.g. couch, panic and ryegrass).

• Every mine in the Hunter Valley should instigate a topsoil management system to record information on all stockpiles located at each site. The database should contain the stripping location, soil type (clay content or sand), stripping depth, machinery used for stripping, date of creation of stockpile, volume and dimensions of the stockpile, seeding mix, priority of use and be identified by a unique number.

• After construction, clearly identify stockpiles with signs to minimise further disturbances and display the date of construction and priority of use.

• Ammonium-N is recommended as an indicator in stockpile storage, as high levels can help.

Rehabilitation Areas

• When respreading soil, aerobic and anaerobic zones formed during stockpiling should be mixed to avoid concentrating or diluting various chemical or biological parameters.

• The machinery used to return stockpiled topsoil affects the level of mixing that can occur. For example, scrapers don't have the ability to mix stockpiled soil as well as trucks and loaders. However, when using scrapers, selective topsoil stockpile portions can be moved from the stockpile, containing relatively equal amounts from aerobic and anaerobic zones. This technique is commonly used in bauxite mining rehabilitation in Western Australia.

• Topsoil stored in taller and some older stockpiles will require the greatest level of amelioration when respread in rehabilitated areas.

• The additional amelioration required following longer storage of topsoil in larger stockpiles is justified if the increased cost of rehabilitation (i.e. application of biosolids at $1,500-2,000/ha; replacing strips of fresh topsoil at $625/ha) is outweighed by the cost saving in stockpiling soil to a greater height.

• Organic ameliorants (e.g. biosolids) are recommended for topsoil stockpiled to medium and larger heights for longer periods of time to provide nutrients, organic matter and contribute to soil stabilisation. However, the proliferation of weed species from biosolids needs to be closely monitored and other organic ameliorants may be more suitable.

• Based on current research within Australia, fresh topsoil should be applied in strips to a depth of 10 cm by scrapers, covering up to 25% of a rehabilitated area that receives soil that has been stockpiled to greater heights for longer periods of time, dependent on soil type. However, for the Hunter Valley further refinement on this technique may be justified with research carried out on the depth of application and the percent cover that is required to provide biological amelioration for effective vegetation establishment.

• Direct return should always be encouraged rather than stockpiling because this involves handling of the soil only once and avoids any further loss of soil quality that may occur during the stockpiling. Putting fresh soil in strips optimises the utilisation of this soil.

• Gypsum should be applied at mines with sodic soil at the rate of 5 t/ha, although specific soil testing should be undertaken to more precisely determine the application rate.

• Stockpiled soil should be spread on rehabilitated sites and seeded immediately to minimise the establishment of weed species through rapid establishment of native vegetation cover.".

It should be noted that this comprehensive research was conducted on topsoils stripped from slopes used for agricultural, including dairy and cropping for over a century. Whether these results apply to 'native' soils stripped from cleared woodlands and forests is not known but unlikely for eastern Australia.

In Western Australian jarrah forests, the presence of propagules of Vesicular-Arbuscular (VA) mycorrhizal fungi was sampled in the topsoil during bauxite mining (Jasper, et al., 1989). These authors observed that the infectivity of propagules in topsoil was destroyed, even when the soil was stripped and respread promptly without stockpiling. Analyses showed that within 3 weeks of clearing the native forest vegetation, before the soil was disturbed, most infectivity was lost. The authors postulated that the rapid loss of infectivity may be associated with the absence of spores in the soil. During the process of rehabilitation, samples of the respread soil showed the infectivity of VA mycorrhizal fungi was substantially greater than that of freshly disturbed soil, but less than levels recorded in similar undisturbed forest soil.

The presence of mycorrhizas, proteoid roots and leguminous nodules was determined in a range of woodland species in the Kakadu area (Reddell P & Milnes, 1992). The authors compared the occurrence of spores of VA mycorrhizal fungi in soils from native woodlands and from revegetated areas on waste rock emplacements from uranium mining. The authors showed that VA mycorrhizal fungi were absent or poorly represented in the stockpiled topsoils and in some of the rudimentary soils formed in waste rock emplacements. In addition, they found that the diversity of spore types and/or numbers of infective propagules of mycorrhizal fungi was lower in stockpiled topsoils and in mine soils than in the undisturbed woodland soils. They concluded that the acute deficiency of P, and to a lesser extent N, was a limitation to growth of seedlings in both natural and waste rock emplacement topsoils. Inoculation of *Eucalyptus pellita* seedlings with spores of the two ectomycorrhizal fungi increased shoot weight by between 20- and 60-fold in comparison with the uninoculated treatment.

Studies of the carbon of stored topsoil associated with coal mining in the United Kingdom was less than the undisturbed reference state areas, and there appeared to be further decreases after respreading (Harris & Birch, 1989). While the trend over time was the carbon levels increased the recovery was not rapid (Harris & Birch, 1989).

Most living vegetative matter present in topsoil when it is mounded is destroyed, reducing the usable source of carbon available (Stark & Redente, 1987). Biomass (organic carbon) stored in stockpiled soils may be present in large amounts, however most microbial diversity was nonviable or dead (Williamson & Johnson, 1990), bacterial spores accounting for the large amounts of this biomass. At greater depths in the stockpiled topsoil higher levels of carbon were found (Williamson & Johnson, 1990), which appears to support conclusion about the base of stockpiles are anaerobic (Harris, et al., 1989).

Reference state

Invertebrate organisms in the top layer of the soil contribute to a complex ecosystem which includes; macrofauna (termites, ants, earthworms), mesofauna (*collembola*, mites), microfauna (nematodes, protozoa), microflora (bacteria, fungi, algae). These organisms perform a wide range of ecological functions: decomposition of organic matter, release nutrients into plant-available forms and degrade toxic materials; form symbiotic associations with plant roots, affect the weathering and increase solubility of minerals and contribute to soil structure and formation (Biswas & Gawade, 2016).

Invertebrate activity is also fundamental to maintaining water infiltration. Eldridge and Freudenberger (2005) showed that by placing water under tension with a disc permeameter, water infiltration under eucalypt trees dropped from 150 mm/hr to less than 30 mm/hr and dropped from 50 mm/hr to less than 10 mm/hr under nearby grass tussocks. It has been shown that by placing water under tension, biological pores greater than 75 micron in diameter are blocked. This simple test demonstrates the importance of biological activity in maintaining high rates of water infiltration.

The majority of vascular plants are associated with mycorrhizal and ectomycorrhizal fungi, which provide benefits from an increased capacity to extract phosphorus and other nutrients from the soil. Mycorrhizal fungi are vital in nutrient cycling, the maintenance of soil structure and in contributing to the process of plant succession and development of plant communities. A large diversity of rhizobial bacteria associated with legumes (e.g. *Acacias*) fix atmospheric nitrogen into plant available nitrogen, a fundamental process of nutrient cycling.

Vertebrates are also important contributors to bioturbation through stirring or mixing the soil, especially by burrowing or digging. For example, the foraging and digging activities of the Southern Brown Bandicoot (*Isoodon obesulus*), digs and stirs-up the soil increasing water and air infiltration into the soil, which benefits plant germination and growth. The decline of Bandicoot and Bettong populations, as a result of the introduction of the fox, is considered to be a contributing factor towards increasingly compact soils in Australia (Nussbaumer, et al., 2012).

Design solutions and leading practices

We conclude from the research on the impact of stockpiling, that it should be avoided whenever possible. Biological activity is consistently and rapidly loss through the stockpiling process.

If stockpiling is unavoidable, the inoculation of seedlings with microbial symbionts may fully or partially overcome particular nutrient limitations. The judicious use of some fertiliser could assist in plant establishment on waste rock emplacements soils to optimise the functioning of the observed symbiotic associations (Reddell P & Milnes, 1992). Given the range of potential nutritional problems and mycorrhizal responsiveness, the authors recommended that more work was needed to characterise these mined soils was necessary to determine the variability in composition of parent rock types and their effects on potential nutritional problems and mycorrhizal responsiveness.

Rehabilitated bauxite waste rock emplacements sites were examined to analyse the recolonization of microbial symbionts over time, compared to the surrounding unmined *Eucalyptus marginata* dominated jarrah forest (Gardner & Malajczuk, 1988). Seedlings of jarrah had been planted over time (providing even-aged stands varying in age from 1 to 7 years old) on the rehabilitated waste rock emplacement site. The authors noted that only a few species of ectomycorrhizal fungi were common to both the unmined and rehabilitated sites. Analyses of the soil and root samples showed a clearly defined succession of ectomycorrhizal fungi was observed as the stands of trees increased in age, the changes being associated with the development of a layer of leaf litter. Numbers of species of ectomycorrhizal fungi observed in the 7-year-old stands were less than half of those associated with the unmined native forest.

The Centre for Sustainable Ecosystem Restoration, The University of Newcastle have identified specificity between local plant species and rhizobia bacteria strains. Inoculated plants have been shown to grow better in certain substrates. Soil can be used as an inoculum of both rhizobia and mycorrhizae, but not all soils are effective for all plant species (Nussbaumer, et al., 2012). The Centre for Sustainable Ecosystem Restoration has been developing a collection, and identifying, a range of native rhizobia from the Hunter Valley that can be cultured and reintroduced. In addition, root cultures of mycorrhizal fungi are being maintained from a number of sites to facilitate scaling up production of these inoculants (Nussbaumer, et al., 2012).

Incorporation of compost as an ameliorant to increase carbon levels can have a significant role in increasing tree growth and survival, and improving soil moisture loss thus making them a valuable resource for mine site rehabilitation. (Kelly, 2008); (Daynes, 2012). At least 3% organic carbon is required to initiate aggregation of spoil fines by plants and mycorrhizal (Nussbaumer, et al., 2012). Sources of appropriate forms of organic carbon in the quantities needed and at the right time periods remains a challenge.

Establishing vegetation cover as soon as practicable following topsoil spreading is also essential (Rawlings, et al., 2010); (Johnston, 2008). Application of a temporary sterile cover crop, or native grass cover crop established by applying native hays and organic mulches (Whitaker, 2016); (Johnston, 2008) has been reviewed above. Seed-bearing mulch may also be used as both the seeding material and an organic additive to the overburden. Several researchers and rehabilitation practitioners (e.g. Groves, et al., 1982; Windsor & Clements 2001; Owen Whittaker pers comm) have used seed-bearing hay collected from a local sward of *Themeda australis* by slashing and raking in January, then air dried and stored the seed-bearing hay for 12 months to overcome seed dormancy.

The area and volume of Themeda seed that is harvested has been increasing over the years as techniques for collecting 'clean seed' at the right time improve in efficiency and as specific areas are set aside and managed for the regular harvest of Themeda seed (Gibson-Roy & Delpratt, 2015; Owen Whittaker pers comm). The optimum seed-to-hay ratio of two seeds per gram of mulch when the seed-bearing hay is firm and brown (McDougall, 1989).

There is considerable potential to utilise native grasses to provide a sustainable perennial groundcover on exposed soils (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008), although it is noted that reliable techniques for the establishment of these grass are still being developed. A high degree of success in germination, establishment and development of native grasses and forbs has been achieved where seed is direct-drilled followed by an aerial application of rice hay spread using a round-bail hay spreader to create a light cover mulch (Whitaker, 2016). The hay provided several benefits; as a medium to stabilise bare soil, to protect the soil from raindrops, to reduce the radiant energy and cool the soil and a source of low nutrient organic matter. As discussed in the previous section cover crops may be used to establish organic content include sorghum, sterile rye and oats.

Implementation risks

Access to, and the use of high quality topsoil brings with it major benefits during critical germination, establishment and development phases of rehabilitation. Soils that have diminished biological activity are likely to hinder these phases. In references sites, care needs to be taken to minimize and avoid the impacts of biological status of the soil including preventing firewood collection or the "tidying up" of fallen dead timber and leaf litter and preventing the stockpiling of topsoil or overburden within remnant areas (refer to Appendix 2).

Knowledge gaps and priority research

We conclude from the research on the impact of stockpiling, it should be avoided whenever possible. Biological activity is consistently and rapidly loss through the stockpiling process. What is less clear is how this loss affects grassy woodland rehabilitation when stockpiled soils are returned to final landforms. Simple field trials testing the effect of spreading freshly stripped compared to stockpiled topsoils is warranted as long as the fresh and stockpiled soils had similar pre-mining properties (e.g. both came from formally wooded or forested soil landscapes).

The degree to which fungal and bacterial levels return to reference status is unknown as is whether the addition of exogenous nutrients at the time of respreading the topsoil over the final landform would enhance the rate of recovery toward the reference state. The detailed soil microbial analyses associated with recreating the Warkworth sands woodland community and native pasture ecosystems (Niche Environment and Heritage, 2016) can be assumed to be seeking answers to the type and magnitude of soil microbial changes which occur during scalping, stockpiling and respreading of the topsoil and to establish where practical methods to redress observed adverse impacts.

Trials of commercially available fungal and rhizobial inoculants should be tested on both freshly stripped native soils and stockpiled soils. We hypothesise that inoculants will be most beneficial in stockpiled soils.

Limited research is available on how the native soil seedbank stripped from forests and woodlands in eastern Australian is affected by stockpiling. (Cole, et al., 2006; Nussbaumer, et al., (2012) working at the Mount Owen Mine found that almost half of the native species found in the Ravensworth State Forest (RSF), a dry sclerophyll forest previously logged and grazed have successfully grown on the spoil placement area primarily through the transfer of forest topsoil and associated seed bank. The Keipert et al. (2004) study focussed on the soil seed bank of agricultural topsoils stockpiled in the Hunter Valley. We predict that viable eucalypt seeds will quickly be lost from stockpiles, but hard seeded acacias may survive, even at depth, particularly if the stockpiles are kept relatively dry.

5. Disturbance regime

Ecological Criterion definition and attributes

All landscapes are influenced by natural disturbances such as periodic fire, flood and drought. Rehabilitation of grassy woodlands needs to reinstate landforms and vegetation that are resilient (recovers) from the local and long-term disturbance regime. These regimes are likely to be changing in response to global climate change. For the northwest slopes and plains of NSW flooding, drought and fires are likely to become more frequent and intense (Office of Environment & Heritage 2014).

Two indicators can be used to encapsulate natural disturbance regimes over time (Table 2).

1. Area or size of disturbance events – the ‘foot print’ of a flood, fire or drought

For example, the aerial extent and patchiness of planned and unplanned fires recorded spatially and temporally in a particular area (Bradstock, et al., 2002). Delimiting the footprints of fire as events over time should be recorded, i.e. the area of vegetation that is burnt and compared to the area of unburnt vegetation within an area of interest. Over large areas this information can be extracted from aerial photography and/or satellite imagery. At site and landscape scales this information may also be collected via on-ground traverses, fire plots and the extent of management zones or compartments that are burnt and not burnt. Other attributes including seasonality and intensity should also be recorded.

Fire scar maps are routinely mapped across Queensland and NSW by the Joint Remote Sensing Research Program. The scale of this mapping is 30 m X 30 m using Landsat satellite imagery. An example is presented here for Queensland (Auscover Remote Sensing Data facility, Queensland Department of Science, Information Technology and Innovation, 2015)

2. Interval between disturbance events

For example, a fire regime is the pattern of fire over a number of years in a particular area and is characterised by: seasonality, frequency, interval between fires, intensity, extent and patchiness (Bradstock, et al., 2002). Delimiting the interval between disturbance events and seasonality and intensity should also be recorded.

Problem definition

All vegetation communities have evolved and are adapted to varying degrees of major natural disturbance regimes, some disturbance events are very destructive e.g. landslides, rock falls, and catastrophic flood, wildfire and cyclones. A major natural disturbance regime in all grassy woodland ecosystems is the local fire regime. However in the last 200 years; use of fire to manage these ecosystems has typically not been used because of issues of close settlement, fodder for livestock and the need to protect life and property. This long absence of fire has contributed to the lack of regeneration of woody species, particularly hard seeded acacias and has likely suppressed the diversity of flora (Penman et al. 2009). Intense rainfall events pose a particular threat to the soil and regolith stability of rehabilitated mined slopes. Yet, such rainfall events, particularly during La Nina high rainfall cycles are likely a trigger for grassy woodland regeneration, particularly for eucalypts as shown by Wilson and Gibbons (2014).

Reference state

It is highly likely that prior to European settlement, periodic burning by natural bushfires and burning by Indigenous people played an important role in the development and maintenance of grassy woodlands (New South Wales Department of Environment, Climate Change and Water, 2010). The frequency of such burning is largely unknown and likely to have been highly variable depending on seasonal conditions, fuel loads and density of Indigenous inhabitants. In some particularly fertile (productive) locations cool season patch burns may have occurred yearly, other locations perhaps once a decade (Bradstock, et al., 2002). Contemporary fire regimes used in the management of plant communities tend to be either of two extremes: plant communities that are rarely burnt or communities that are burnt by unplanned wildfire that is mainly late in the driest season (Bradstock, et al., 2002). Neither of these strategies is beneficial for the long-term management of grassy woodlands. What is not disputed is that fire has been an integral part of grassy woodlands for millions of years. Prescribed burning can reduce dominance by Kangaroo Grass and prevent in inter-tussock space build-up of plant litter, stimulating germination, growth and flowering of other native species (Stuwe J & Parson, 1977).

Examination of the response of grassland structure and composition post fire, at a site on the South West Slopes, NSW did not result in sward collapse during 14 years of monitoring (Prober, et al., 2007). This research also showed that the Kangaroo Grass/Snow Grass understorey is most resilient to various fire regimes when both species remain in moderate abundance (Prober, et al., 2007). This grassy groundcover was found to regenerate well with autumn burning cycles approximately every 5-8 years, where this had historically occurred (Prober et al. 2008). However, Snow Grass does not recover as rapidly as Kangaroo Grass after burning, and the relative dominance of these two grasses in remnants appears to be regulated by the fire frequency (Prober, et al., 2007). Such high frequency burning cycles may negatively impact other native species, however, and further research is required before burning regimes can be explicitly determined (Department of Trade and Investment Regional Infrastructure and Services, 2013). Too frequent or extensive burning may limit recruitment of some species, cause local extinctions of fire sensitive species, facilitate the spread of some exotic species (such as Coolatai Grass), reduce fauna habitat features (fallen logs, hollow trees, litter) and threaten fauna populations (New South Wales Department of Environment, Climate Change and Water, 2010). In contrast, the lack of fire in Australian temperate grasslands can lead to sward collapse and weed invasion (Morgan & Lunt 1988).

Intense rainfall events also shape grassy woodlands and are surprisingly frequent. For example, Hannan's (1985) analysis of NSW rainfall records shows that rainfall intensities of 140-150 mm/hr for 10 minute durations occur at least once in every 10 years. Such rainfall intensities are likely readily absorbed in highly functional woodlands with steady state infiltration rates of 150 mm/hr under mature eucalypts, but such intense rainfall would likely lead to significant runoff and the risk of erosion if infiltration rates are less than 10 mm/hr as found in bare fields (Eldridge and Freudenberger 2005).

Design solutions and leading practices

Use of prescribed fire to enhance rehabilitation of grassy woodlands on mined surfaces in eastern Australia is largely untested. Since few mines have ceased operations, fire poses a high risk to built infrastructure and exposed coals seams. However, either wildfire will burn rehabilitated sites, or prescribed fire will be used to reduce fuel loads and enhance ground cover diversity. If wildfire burns relatively young grassy woodland rehabilitation (less than 10 years old), long-term effects are likely to be minimal given the monitored results aftermath of the 2003 Canberra fire storm on revegetation. Research by Pickup et al. (2013) found that burnt revegetation showed high (>60%) post-fire survival, but this varied among species depending on the regeneration strategy (obligate seeder or resprouter). The native ground cover, mid- and overstorey in both types of plantings showed rapid recovery of vegetation structure and cover within 3 years of fire. This recovery was similar to the recovery in burnt remnant woodlands. Non-native (exotic) ground cover initially increased after fire, but was no different in burnt and unburnt sites 5 years after fire. Indices of soil function in all types of vegetation had recovered to levels found in unburnt sites 5 years after fire. These results indicate that even young revegetation (stands <10 years old) showed substantial recovery from disturbance by fire. Similarly, we note that ALCOA working regenerating eucalypt dominated ecosystems associated with bauxite mining, has undertaken trial fire events in rehabilitation sites up to 20 years old. Where eucalypts are used in revegetation, and provided they have developed a lignotuber, their ability to survive even intense fires is widely acknowledged (Fensham, et al., 2008; Bell & Williams, 1997).

Design solutions and leading practices for reducing the disturbances caused by intense rainfall events are reviewed under Ecological Criteria 1-4 above.

Design solutions for managing the risk of drought is reviewed under Criteria 9 and 10 below (overstorey and understorey diversity).

Implementation risks

Care needs to be taken to minimize the impacts of major disturbance events during critical germination, establishment and development phases (refer to Appendix 2). In reference sites, care needs to be exercised to allow survival of soil and ground fauna (including invertebrates, amphibians and reptiles) and promote diversity in the states of the ecological community. Some unburnt areas should be retained to provide refuges for species of fauna and flora that may be intolerant of fire. An awareness of the areas to be burnt and the frequency of ignition should adapt a minimum fire interval suggested for Box-Gum Grassy Woodlands of five years, with a maximum interval of 40 years (Department of Trade and Investment Regional Infrastructure and Services, 2013).

In young restoration and reconstruction areas, unplanned fire could eliminate the juvenile and maturing plants. If a seed bank has not been established, it may eliminate species from an area (Nussbaumer, et al., 2012).

Knowledge gaps and priority research
Further research into the role of fire to enhance the diversity of persistence of grassy woodlands need to continue, but at this point in time, is most relevant to the management of remnants of grassy woodland, for instance those found in offset areas established by the mining industry. In the fullness of time, the role of fire based on research on remnants can be applied to rehabilitated mine sites when operations and infrastructure are removed at closure. Research in offset areas would be particularly useful if it is undertaken in woodland systems dominated by grass species such as Redgrass (*Bothriochloa macra*), Wallaby Grass (*Austrodanthonia* spp.) and Speargrass (*Austrostipa* spp.) as little fire research has been conducted on these types of understories (Prober, et al., 2007).

6. *Reproductive potential*

Ecological Criterion definition and attributes
The natural reproductive or regenerative potential of any vegetation system can be enhanced, maintained, limited or removed through land management practices. The long-term goal of mine rehabilitation of grassy woodlands should be to create functionally, structurally and compositionally diverse woodland that self regenerates with minimal human input. This starts with good top soil management as described below.

The regenerative capacity of a grassy woodland can be rapidly assessed by quantifying the presence of regenerating growth forms and age classes of growth forms of dominant structuring species found in the overstorey and understorey. Hnaituk et al. (2009) describes widely used field methods to quantify regeneration of vegetation strata.

Problem definition
Reproductive potential of the dominant structuring species describes the inherent natural regeneration of a plant community in the overstorey and understorey. In early phase rehabilitation the reproductive potential of most woodland overstorey species is removed because seeds, in particular eucalypts, generally do not survive being stored in topsoil mounds (Buckney & Morrison 1992; Bell 2001). To reestablish the reproductive potential of most overstorey eucalypt species it is necessary to plant seedlings or sow viable seed. In contrast acacias may survive being stored in topsoil mounds (Figure 5) depending on time stockpiled. The degree to which ground cover species are reestablished from the soil seedbank of mine soils, rather than re-planting, is recognized as a very low recovery (Collins & Brundrett, 2015; Koch 2015.

Reference state
Unhindered reproductive potential of grassy woodlands is characterised by the presence of various age structures or cohorts of woody plants and the presence of recruitment of herbaceous species in the understorey. In quality reference sites there should also be viable seed in the soil as well as vegetative structures (e.g. lignotubers) which can rapidly reestablish the plant community after disturbance events such as fire.

The reproductive potential of reference sites can be enhanced by the judicious use of fire as reviewed under the previous Criterion (Disturbance regimes). In short, an appropriate fire regime, particularly the timing of burns must be considered in relation to the flowering and seeding of native and exotic species. Where possible burns should be carried out after natives have seeded but before weeds flower and seed (Appendix 2).

In references sites, care needs to be taken not to impinge on the reproductive potential of the overstorey and understorey. Some key factors include limiting total grazing pressure from domestic, feral and native herbivores at critical flowering and seeding periods for ground cover species. Reducing total grazing pressure during drought periods may be particularly important (Dorrough et al. 2004).

Design solutions and leading practices

The reproductive success of key structuring species that are naturally found in the overstorey and understorey can be enhanced and maintained through sound soil preparation, direct drilling species and replanting tube stock. These practices are reviewed in detail under Criteria 9 and 10 (composition).

As noted in the previous section, a cover crop of <u>fertile</u> exotic grasses and sorghum should not be planted on a topsoil mound which has a high integrity for native vegetation. This is likely to contaminate the mound and the future soil that will be used for re-establishing native vegetation (Field, 2016)

Implementation risks

Re-instating the reproductive potential of grassy woodlands during the initial phase of rehabilitation is reviewed under other Criteria. A long term as well as short term risk is overgrazing by poorly controlled domestic, feral and native herbivores. An additional long-term risk is the re-planting of species provenances with poor genetic diversity (e.g. inbred) that fail to flower and reproduce well, or re-planting with insufficient provenance diversity to cope with a rapidly changing climate. Managing these risk is reviewed under Criteria 9 and 10 (composition).

Knowledge gaps and priority research

The long term capacity of woodland trees, particularly eucalypts to self-regenerate on rehabilitated mined surfaces is unknown. Mine rehabilitation is generally too young to assess the reproductive potential of keystone eucalypt species. Long-term monitoring is needed is determine when dominant overstorey species begin to flower, how frequently they flower and the viability of the seed set.

Research that can begin at the time of rehabilitation plantings should examine the natural reproductive potential of short lived species, particularly ground cover grasses and herbs. The hypothesis is that the herbaceous understorey can self-regenerate in a matter of a few years depending on seasonal conditions, lack of weeds and low grazing pressure. The converse hypothesis is that ground cover regeneration is impeded by competition from exotic species sustained by overly high soil fertility and suppressed by high grazing pressure.

Structural criteria

These criteria, applicable to any vegetative ecosystem describes the vertical and horizontal arrangement of living and dead plants from the overstorey to the ground covers including standing and fallen timber. These are dynamic features of vegetation communities, but communities are never the less classified into forests, woodland, shrub lands and grasslands by the distinctive structure of these broad types of vegetation.

7. Overstorey structure

Ecological criterion definition and attributes

Overstorey structural diversity is the spatial arrangement of trees. It can be measured in various ways including: stem density/ha, a diversity of age classes of the stand, frequency distribution of stem sizes (e.g. diameter of breast height), density of standing dead timber, or canopy area and volume. These measurements can be made within fix plots or by the use of plot-less techniques described in Hnatiuk et al. (2009) and Tongway and Ludwig (2011). Indices of structural complexity for assessing vegetation condition (e.g. Parkes et al 2003; McElhinny et al. 2006) commonly refer to fallen logs and stags as habitat features.

Problem definition

Rehabilitating the appropriate density of trees is a significant challenge. Too few trees and there is insufficient habitat for tree dependent biota and too few trees is likely to reduce the topsoil and regolith stability provided by tree roots. Too many trees can outcompete understorey plants that provide considerable protection from rain splash impact leading to excessive runoff and erosion (Tongway and Ludwig 2011). Figure 6 is an illustration of this impact on ground cover caused by an overly high density of trees compared to a much more open overstorey structure on a nearby rehabilitated slope.

Figure 6. A high density of trees (left photo) can suppress ground cover vegetation well established on a nearby slope (right photo). Both slopes are rehabilitated final landforms at a coal mine in the Gunnedah region of NSW.

Reference state

Unmodified grassy woodlands (Table 1) are characterized by a relatively open structure of trees in the overstorey. In its unmodified form the crowns of the overstorey trees are clearly separated with a canopy cover between 20-50% ((McIntyre, et al., 2002) (Hnatiuk, et al., 2009a) (Yates & Hobbs, 1997)).Grassy woodlands in their reference state typically have widely spaced trees with an average of 20 mature trees 20-40/ha (Australian Government, Department of the Environment, n.d.) (Rawlings, et al., 2010). Tree heights of 5-20 m are common (Hnatiuk, et al., 2009a). The number of trees will likely be lower where annual rainfall is below 500 mm and higher where rainfall is above

500 mm (Rawlings, et al., 2010). The presence of an even mix of tree growth stages 1-5 (Figure 7) at the stand level is not a characteristic of *Unmodified* grassy woodlands.

In a comprehensive field survey and literature review by Gibbons et al. (2010), they found a density of 23 trees per ha for stems >40cm DBH. Other studies reported in this review included average pre-European densities of 47, 189 and 472 trees >20cm DBH per ha in open woodlands, woodlands and open forests respectively. On relatively unmodified roadsides dominated by grey box in northern Victoria, 63–84 trees per ha between 31–70cm DBH and 20–21 trees per ha >70cm DBH were reported. From surveyors' records, woodlands in the study area contained 6–31 trees per ha >30–40cm DBH.

A minimal cover abundance of tree growth stages 1-3 (Figure 7) typical of *Unmodified* grassy woodlands, is a reflection that land management interventions have a controlling influence of recruitment. *Unmodified* grassy woodlands are in fact a managed landscape, created and maintained by Aboriginal land management (i.e. fire) and after European settlement this same structural diversity of the overstorey was maintained by total grazing pressure. Recruitment of tree growth stages (i.e. age cohorts) into the overstorey can usually be explained by a combination of land management and natural disturbance histories and long term climate patterns. Recruitment of tree growth stages is critical to the long term ecological integrity of grassy woodlands. As a rehabilitation area develops, evidence should be apparent of the germination, establishment and development of different age class cohorts of trees.

The relative proportion of growth stages of trees present at a site will change as woodland rehabilitation develops. In sparse vegetation, 'woodland' trees are similar in shape to those in growing in mid-dense and closed vegetation ('forest' trees), but the overall tree-form is shorter and wider (Hnatiuk, et al., 2009a), refer to Figure 7.

Where more intensive land management practices have retained some the characteristic features of the overstorey, but there has been clearing and thinning for grazing, this has resulted in either a much reduced tree cover producing open woodlands or isolated trees (with a canopy cover of less than 20%) or removal of the overstorey trees altogether creating derived native grasslands (New South Wales Department of Environment, Climate Change and Water, 2010). These modified condition states correspond to *Transformed* (Table 1; (Thackway & Lesslie, 2008).

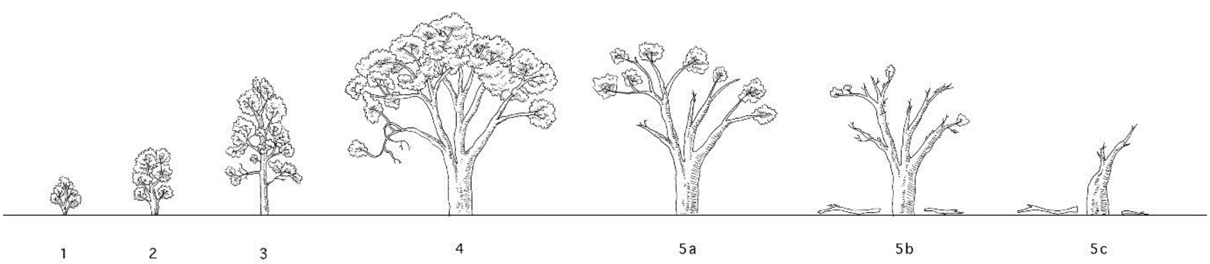


Figure 7. Typical woodland tree growth stages that comprise structural diversity. The numbers underneath refer to growth stage of woodland trees (Hnatiuk, et al., 2009b). The expected occurrence of these growth stages in the five woodland rehabilitation phases are presented in Table 3.

Design solutions and leading practices

If topsoil used for covering final landforms has been stockpiled, it is most likely that little eucalypt seed will have survived, though some acacia species, in the soil seed bank may still be viable. Therefore, during the *early rehabilitation phase* shown in Table 3, it is important to consider how to reconstruct an appropriate overstorey structure (density and ages). For eucalypts in particular this will likely need to occur through sowing of seed, or preferably planting of seedlings established in a nursery.

Table 3 provides a summarised guide for an appropriate woodland overstorey structure through time. As a rehabilitation area establishes and develops in the longer term (decades and centuries), evidence of multiple tree growth stages that comprise structural diversity (i.e. a diversity of age classes within the stand) should be observed, if natural regeneration occurs. At the outset of rehabilitation, these future rehabilitation development phases that are described in Table 3, can be regarded as 'expected'.

Since reference conditions for woodland structure is so open, a planting rate of no more than 50 eucalypts per ha is likely to be adequate to achieve benchmark stem densities assuming limited mortality. Note planting at 15 m between rows and 15 m along rows equates to 40 trees per ha. At such a low planting density, it is justifiable to invest in maximising the survival of each tree seedling. The use of tree guards can reduce mortality from desiccation, severe frost and browsing animals (Graham et al. 2009). In topsoils severely depleted of organic matter (e.g. rock quarries), the addition of one litre of quality compost placed in the planting hole has been shown to be a critical procedure for ensuring high survival and growth of tree and shrub seedling planted into harsh conditions (McPhee 2013).

Rawlings et al. (2010) provide guidelines in securing a supply of quality seedlings for reinstating an appropriate open woodland structure. Ordering seedlings well in advanced and grown by a reputable nursery using square cells rather than round tubes, and hardened off out doors are all important practical steps in reducing the risk of establishment failure. Quality seedlings requires quality seed and this issue is reviewed under Criterion 9 (overstorey composition).

Eucalypts can be established by direct seeding machinery (Rawlings et al 2009). This can be a cost effective technique if a high density of trees (eucalypts and acacias) is desired (e.g. a shelter belt). However, for creating an open woodland structure to benchmark densities of less than 50 eucalypts/ha, direct seeding unlikely to be cost effective. If direct seeding is used and tree establishment is too dense, a thinning operation could be implemented. This is an added expense, but thinned trees can immediately create significant loads of course woody debris that contributes to improved ground cover structure and function.

Another implementation approach is to combine direct seeding of short lived (10-20 years) acacias with planting of nursery grown eucalypt seedlings. Direct seeding of acacias is likely to be cost effective as their seed is usually less expensive and can remain in the soil seed bank for a number of years until suitable seasonal conditions occur for germination. If the acacias establish at high density, it appears, at least in the Southern Tableland of NSW that eucalypt seedlings seem to cope well, or even benefit from being in amongst a high density of acacias (person observations). High densities of acacias may not be a common feature of reference condition grassy woodland, but they either get grazed out by herbivores or rapidly die off and decay in 20-30 years. Establishing a high density of acacias on mined slopes may contribute to slope stabilisation (dense shallow roots), fix nitrogen and add surface carbon through leaf fall and tree fall.

Implementation risks

Numerous factors can affect the likelihood of success in rehabilitation of overstorey structural diversity. High mortality rates of planted or sown seeds can be caused by drought, weed competition or damage by browsing mammals or insects. The disadvantage of using nursery grown seedlings is that they have to be planted at time of delivery from the nursery. They cannot be held over very long in the nursery otherwise they will become root bound. Hand watering of tree seedlings is warranted if there is limited soil moisture at time of planting. If planting at low densities (e.g. 50/ha), the cost of hand watering is justifiable.

Too dense a planting is likely to prevent early phase recruitment until the crown opens-up and this could take decades. Where row spacings are too narrow trees will form a forest rather than a woodland (Figure 6 above). Row spacing of the trees is also critical when considering whether mechanical weed control maybe necessary during establishment of seedlings and saplings. Controlling total grazing pressure may also be required where invasive vertebrates may prove a hindrance due to browsing and rubbing. Tree guards may be warranted.

In references sites, care needs to be taken not to adversely impinge on the overstorey structural diversity (i.e. a diversity of age classes) of the stand. Managing recruitment is important. Where there is a perceived need to encourage recruitment of tree growth stages 1-3 (Figure 7) into the overstorey it will be necessary to manage this process. Some key factors affecting recruitment include limiting total grazing pressure at critical periods of setting of seed and reducing total grazing pressure during drought periods. Implementing time-based cell grazing may provide beneficial solutions to achieve germination and recruitment of tree species (refer to Appendix 2). In addition, removal of senescent trees, course woody debris and standing stags (i.e. tree growth stages 5b and 5c, Figure 7) should be discouraged unless it is appropriate to stimulate the recruitment of tree growth stages 1-3 (Figure 3) into the overstorey.

Knowledge gaps and priority research

Field trials are needed to examine cost effective planting designs and technologies. The financial and environmental benefits and costs of combining hand planting of a low density of eucalypts with direct seeding of acacias needs to be investigated. The design of row spacing needs to modelled and field tested to allow for mechanical weed spraying, direct seeding of acacias, broadcast seeding of ground covers as well as planting of widely spaced eucalypts. At the same time row spacing (e.g. mounds) should be modelled and tested to reduce the risk of erosion, but facilitate small-scale runoff that can enhance tree survival and growth (Tongway and Ludwig 2011).

Table 3. Expected structural diversity in five woodland rehabilitation development phases described at the stand level using overstorey woodland tree growth stages, understorey and ground layers.

	Structural diversity expected at the stand level			
Five woodland rehabilitation development phases	*Overstorey strata - trees dominant*	*Understorey strata - shrubs dominant*	*Ground layer - grasses and herbs dominant*	*Ground layer -_ cryptogams (mosses and lichens)*
Early rehabilitation phase	Dominated by small, juvenile, dense to very sparse regenerating or planted seedlings (growth stage 1); Dead trees/stags (growth stage 6) and logs are strategically located and positioned mechanically.	Dominated by small, juvenile, dense to very sparse regenerating plants.	Plants small and juvenile stages predominate.	Plants are absent. Very high levels of bare ground and/or mulch common.
Advanced rehabilitation	Dominated by dense to sparse, well-developed, immature plants (growths stage 2 & 3). Trees have well-developed stems (poles). Crowns have small branches. The height is below maximum height for the stand type. Apical dominance still apparent in vigorous trees.	Dominated by dense to sparse, well-developed but not mature plants. If large emergent plants are present, then they occupy <5% crown cover of the dominant stratum; if >5%, classify as 'uneven age'.	Perennial vegetative growth abundant; plants approaching full mature size but reproductive material absent or in early stages only.	Thin growth of young plants or widely spaced clumps of young plants. Some reproduction may be evident. Moderate to high levels of bare ground and/or mulch common.
Uneven age rehabilitation	Mixed size and age classes, usually identified by two or more strata dominated by the same species, but can also be sites with different species regenerating in the understorey of an older canopy (growth stages 1, 2, 3 & 4). Reproduction and regeneration common at appropriate seasons of year or drought/rain cycle; overall health and vigour high.	Mixed size and age classes; usually two or more strata dominated by the same species, but includes sites with different species regenerating in the understorey of an older canopy. Reproduction and regeneration common at appropriate seasons of year or drought/rain cycle; overall health and vigour is moderate to high.	A mixture of mature, perennial and immature annual species present on site. Reproduction and regeneration common at appropriate seasons of year or drought/rain cycle; overall health and vigour is moderate to high.	A mixture of mature and immature annual species present on site. Reproduction and regeneration common at appropriate seasons of year or drought/rain cycle; overall health and vigour is moderate to high. Bare ground largely obscured in average sites
Mature phase rehabilitation	Mature-sized plants with some crowns touching (growth stage 4), with or without emergent senescent plants (growth stage 5). Trees at maximum	May have well-spaced mature-sized plants, or have very densely packed plants with crowns touching, with or without emergent senescent plants.	Most plants of reproductive age; depending on vegetation type, reproduction common at appropriate seasons of year or drought/rain cycle;	Swards of plants common; plants of mature physiognomy (clump sizes and forms); appropriate seasons of year or drought/rain cycle; overall health and

	height for the type and conditions. Crown at full lateral development in un-locked stands. No apical dominance. Small and medium hollows present. Reproduction and regeneration common at appropriate seasons of year or drought/rain cycle; overall health and vigour high.	Reproduction is low to moderate at appropriate seasons of year or drought/rain cycle; overall health and vigour high.	overall health and vigour is moderate to high.	vigour is moderate to high. Bare ground largely obscured in average sites
Senescent phase rehabilitation	Dominated by over-mature plants (growth stage 5) particularly in the dominant stratum; evidence of senescence in many plants, some without obvious links to disturbance. Tree crowns show signs of contracting: dead branches and decreased crown diameter and leaf area. Distorted branches and burls may be common. Large hollows present. Some large fallen branches. Dead trees and fallen stags may be present. Reproduction and regeneration declining or absent at appropriate seasons of year or drought/rain cycle.	Dominated by old plants (thick stems and primary branches, crowns either extremely dense with much dead wood or thin and open if species sheds dead branches), particularly in the dominant stratum. Many senescent plants, some without obvious links to disturbance. Shrub cover sparse to very sparse. Reproduction is very low to moderate at appropriate seasons of year or drought/rain cycle; overall health and vigour high.	In largely annual vegetation, reproduction is complete and plants are dying or mostly dead; in perennial vegetation, plants have lost vigour, are breaking down; large areas of soil are exposed. Dead clumps of tussocks common. Litter accumulation may be high. Reproduction is low to moderate at appropriate seasons of year or drought/rain cycle.	Clear evidence of the degeneration of plants or clumps; dead older parts of plants may be conspicuous. Some reproduction present at appropriate seasons of year or drought/rain cycle. Bare ground increasing in average sites.

Modified from Table 28 in (Hnatiuk, et al., 2009a).

8. Understorey structure

Ecological criterion definition and attributes

This criterion is defined as the density, relative proportion, aerial extent (cover), size (e.g. height or basal diameter) and age distribution of shrubs, grasses and forbs. It can also include the cover of cryptogams (mosses, lichens, bryophytes and bacterial crusts). Understorey structure also includes the cover and density of fallen timber, surface rocks and the cover and depth of finer dead plant material (litter). Standard methodologies to measure structural attributes of grassy woodland understorey is provided in Hnaituk et al. (2009).

Problem definition

Recruitment of understorey growth forms, including dead plant material are critical to establishing and developing the long term ecological integrity of grassy woodlands (Table 3). As a rehabilitation area develops evidence should be apparent of the germination, establishment and development of different age classes and sizes of understorey species.

Reinstating a structurally diverse grassy woodland understorey remains a major challenge for mine rehabilitation. To date most attention has been on establishing a woody overstorey, often with outcomes that are far too dense to be defined as a woodland structure. Establishing a structurally diverse native understorey is just as important and proving to be more difficult. A structurally diverse understorey provides vital ecological functions particularly soil stabilisation, nutrient cycling and water infiltration (Tongway and Ludwig 2011). Diverse understorey structure also provides vital habitat for ground dwelling wildlife such as lizards and a diversity of ground feeding birds.

Reference state

Understorey structural diversity of grassy woodlands is characterised by native tussock grasses, herbs and scattered low shrubs (where shrub cover comprises less than 30% cover) (Department of Environment, Climate Change and Water, NSW, 2010).

Shrubs may be present with a generally sparse or patchy distribution but may become dominant over a localised area (TSSC 2006; Prober and Thiele 2004). On poorer soils, Box-Gum Grassy Woodlands grades into shrubby woodlands (Prober & Thiele, 1993).

In *Unmodified* and *Modified* woodlands and derived native grassland (i.e. grassy woodland where the tree overstorey has been removed), the relevant understorey criteria that are required for listing of a Grassy Box Woodland includes that sites must have:

- have a predominantly native understorey (i.e. more than 50% of the perennial vegetative ground layer must comprise native species), and
- be 0.1 hectare (ha) or greater in size and contain 12 or more native understorey species (excluding grasses), including one or more identified important species defined in Appendix 1 of that report (New South Wales Department of Environment, Climate Change and Water, 2010)

These condition states correspond to VAST class I/II (Table 1).

Within high condition grassy woodlands in south eastern Australia, Kangaroo Grass often dominates open areas, while Snow Grass tends to dominate under trees. The abundance of both grasses is generally lower under trees facilitating the establishment of subsidiary species (Prober, et al., 2002). However, these tussock grasses can dominate and outcompete forbs and small grasses if unburnt or ungrazed for long periods of time (decades).

Where less intensive land management practices have been used to produce more productive pastures, the overstorey is present but the native grassy ground layer has been removed and/or modified by pasture improvement, such that the ground layer is now dominated by mixed native and exotic species (McIntyre, et al., 2002; Cole et al., 2006). These condition states correspond to *Transformed/ Adventive* classes (Table 1).

Ground layer cover includes a vegetation component but also includes cover of rock, cryptogams, litter and bare soil. In an *Unmodified* woodland there is characteristically a total ground cover of native grasses, forbs and litter (Table 3). If there are small areas of bare ground, they are usually covered by a diversity of cryptogams (Eldridge et al. 2006).

Unmodified sites also have considerable fallen timber (coarse woody debris) in a diversity of widths and lengths.

Design solutions and leading practices

Leading practices to rehabilitate a structurally diverse understorey of vegetation is reviewed under the Criterion 10 (Understorey composition). In short, it is important to select framework or dominant structuring species to achieve benchmark ground cover, heights, basal diameters and densities. Native perennial tussock grasses, both summer and winter active species, should always be a major component of ground cover structure. Short and tall shrubs may also be key structuring species depending on soil types, slopes and what is found in local reference sites.

In the early phases of rehabilitation of Grassy Box Woodland particular care will be required to limit total grazing pressure at critical flowering and seeding periods for ground cover species and reducing total grazing pressure during drought periods. Post mine closure, or possible sooner, implementing an appropriate fire regime, particularly the timing of burns may need to be considered in relation to the flowering and seeding of native and exotic species. Where possible burns should be carried out after natives have seeded but before weeds flower and seed.

In references sites, care needs to be taken not to impinge on the structural characteristics of the understorey. Some key factors include limiting total grazing pressure at critical flowering and seeding periods for ground cover species and reducing total grazing pressure during drought periods. Implementing time-based cell grazing may provide beneficial solutions to achieve better balances in densities of tussock grasses and forbs. Also using an appropriate fire regime, particularly the timing of burns must be considered in relation to the flowering and seeding of native and exotic species. Where possible burns should be carried out after the framework species have seeded but before weeds flower and seed. (refer to Appendix 2).

Leading rehabilitation practice for understorey structural diversity also includes, where possible, the addition of patches of dead timber, often salvaged from woodlands or forests being cleared for mining. Stockpiling of salvaged timber should also be considered when direct transfer from a source site to a rehabilitation site is not practical. The NSW Biometric vegetation benchmarks specify 30m fallen timber for Grassy White Box Woodland in the Namoi catchment (Department of Environment, Climate Change and Water, NSW, 2010).

If available from mining operations and found in local reference sites, a diversity of stable (inert) rocks should be added in patches. Surface rocks have been shown to be important wildlife habitat, particularly for reptiles (Michael, et al., 2010).

The establishment of cryptogamic crusts to date relies on natural recruitment, probably from spores blown onto a rehabilitation site. However, management does have an important role in cryptogamic establishment. It critical to minimise soil disturbance. Cryptogams tend not to establish on lose or eroding soil surfaces (Tongway and Ludwig 2011). Hence the importance of quickly stabilising applied top soils and constructed regoliths as reviewed under Criterion 1 (soil physical status). It is also important to control total grazing pressure and vehicular movements that can disrupt the establishment of cryptogamic crusts.

Implementation risks

There are probably few ecological risks associated with the addition of fallen timber and inert rock, except for the risk of soil compaction by machinery used to place these materials. Rock piles should be placed prior to final deep ripping and topsoil placement. Salvaged timber can probably be placed with limited compaction if soils are dry and the lightest practical machinery used.

The risks involved in establishing a structurally diverse flora is summarised under Criterion 10 (understorey composition). In short there is considerable risk of establishment failure due to weather conditions, poor quality seed, inadequate quantities of seed, and poor placement of seeding.

Knowledge gaps and priority research

We are not aware of any research that has demonstrated the ecological value of installing fallen timber on mine rehabilitation slopes, though this long-term research is being conducted within reference condition grassy woodlands in the ACT. We hypothesise that it may take at least 10 years or more for artificially place fallen timber to be colonised by at least some common species of wildlife. It is also worth setting up a field trial to investigate the effects of two contrasting strategies to distribute equal volumes of fallen timber – clumps vs scattered. A similar study of placing clumps or a scatter of inert rock should be conducted on those mines with such rocks.

Research trials to improve the structural diversity of ground cover vegetation is recommended under Criterion 10 (understorey composition).

Compositional criteria

9. Overstorey composition

Ecological Criterion definition and attributes

This criterion describes the composition of woodland overstorey in two ways, the identity of species in the overstorey (species composition) and the allocation of these woody species into functional groups. Common field methods to record species composition is found in (Hnatiuk, et al., 2009a).

Overstorey and midstorey species functional groups include: canopy trees, understorey trees, woody shrubs, and introduced woody shrubs (Cummings & Reid, 2008). Land use and management practices maintain or modify the number and densities of species functional groups. Changes made to species functional groups generally reflect the values of a land manager and of the wider society. Depending on a land manager's goal/purpose for managing a site, various mixes and densities of these functional groups of the native vegetation are maintained, modified, removed and/or replaced. The dominance of particular species in *Unmodified* sites provides valuable clues about overstorey and midstorey species functional groups.

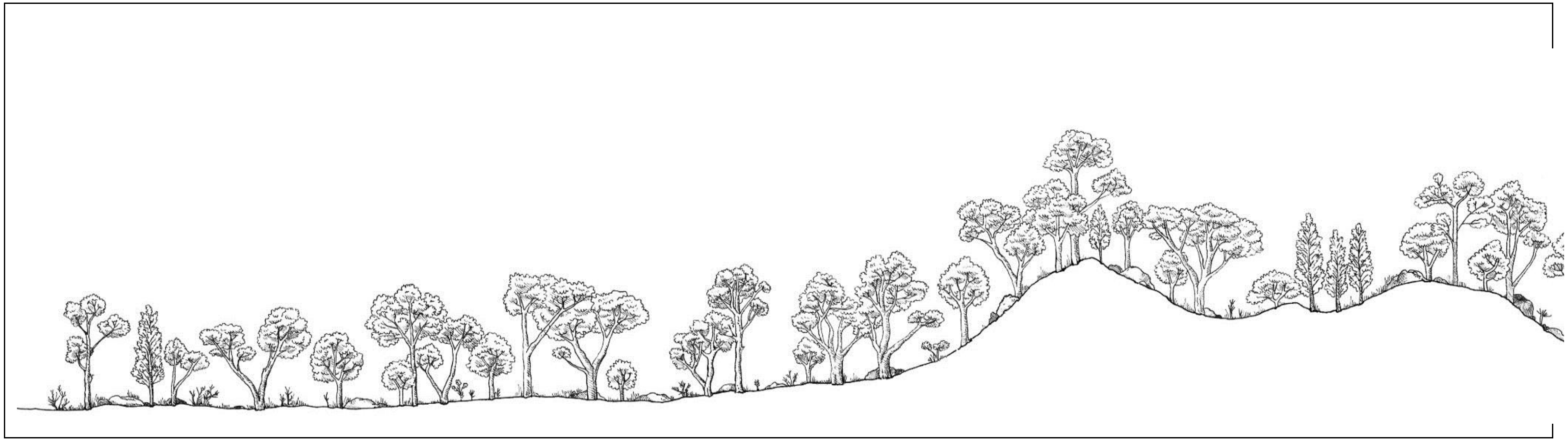
Problem definition

The objective of grassy woodland rehabilitation should include the reinstatement of locally native overstorey species to appropriate positions along slopes with varying soil depths, texture, water holding capacity and other characteristics (Figure 8). This can be problematic for mine sites where the final landform is constructed to relatively uniform and moderately steep slopes (e.g. 10^o) and with a novel regolith of mined overburden. The overstorey species present prior to mining may not be a fully suitable reference. For instance, a mine might remove a lowland grassy woodland growing on deep outwash (alluvial) soils with a high clay content and 3^o slopes. This lowland woodland is unlikely to have supported trees species that grow well on final mined landforms of 10^o slope and with a freely draining regolith composed of tertiary marine sediments. Woodland or open forest communities further up a local catena may provide a more appropriate composition of tree species to establish on mined slopes. The original lowland woodland may be still be an appropriate reference only for those areas of the mine that are least disturbed, have maintained the original low gradient slopes and have an intact 'native' regolith (e.g. areas of infrastructure decommissioned at closure).

Reference state

It is widely acknowledged that, compared to many other plant communities, grassy woodlands exhibit a much higher number of species in the understorey rather than the overstorey (Table 4). Table 4 summarises the species list for White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Ecological Community that was developed to complement the Listing Information Guide for this plant community under the *Environment Protection and Biodiversity Conservation Act 1999* (Department of the Environment, n.d.)

In an *Unmodified* grassy woodland, almost 70% (n=403) of species are non-woody species; and of this total over 55% are herbs, 9% are grasses, which are found in the understorey or ground layer. The woody growth forms including; trees, shrubs, shrub/tree growth forms found in the overstorey and mid-storey make up the remaining 30%; with trees comprising less than 6% (n=34), shrubs around 21% (n=126) and shrub/ tree less than 4% (n=23).



Landform	Gently undulating rises	Hills	Crests and ridges
	Community 3. White Box – White Cypress Pine Grassy Woodland (Bower 2011,Table 10)	**Community 2. White Box – White Cypress Pine Shrubby Woodland (Bower 2011,Table 9)**	**Community 1. White Cypress Pine - Narrow-leaved Ironbark Shrubby Open Forest (Bower 2011,Table 8)**
Landscape position:	Gently undulating hills on soils of the Maules Creek Formation.	Mid slopes and drainage lines of the Willowtree Range	Upper slopes and hill tops of the Willowtree Range
Vegetation type	Grassy Woodlands	Dry Sclerophyll Forests (Shrub/grass subformation)	Dry Sclerophyll Forests (Shrubby subformation)
Plant Community	White Box - White Cypress Pine shrub grass hills woodland in the Brigalow Belt South and Nandewar Bioregions (NSWVCA community 435).	White Box - White Cypress Pine shrubby hills open forest mainly in the Nandewar Bioregion (NSWVCA community 588)	Narrow-leaved Ironbark - Cypress Pine - White Box shrubby open forest in the Brigalow Belt South and Nandewar Bioregions (NSWVCA community 592)
Trees	White Box (Eucalyptus albens)	White Cypress Pine (Callitris glaucophylla)	Narrow-leaved Ironbark (Eucalyptus crebra)
	White Cypress Pine (Callitris glaucophylla)	White Box (Eucalyptus albens)	White Cypress Pine (Callitris glaucophylla)
	Poplar Box (Eucalyptus populnea)	Wilga (Geijera parviflora)	White Box (Eucalyptus albens)
	Rosewood (Alectryon oleifolius)		White Bloodwood (Corymbia trachyphloia subsp. amphistomatica).
			Motherumbah (Acacia cheelii)
			Wilga (Geijera parviflora)
			Quinine Bush (Alstonia constricta)
			Weeping Pittosporum (Pittosporum angustifolium)
Shruhs	Water Bush (Myoporum montanum)	Cassia (Senna form taxon 'zygophylla')	Cough Bush (Cassinia laevis)
	White Cypress Pine (Callitris glaucophylla) juvenile	Sticky Hop-bush (Dodonaea viscosa subsp. spatulata)	Yellow-berry Bush (Maytenus cunninghamii)
	Small-leaf Bluebush (Maireana microphylla)	Western Silver Wattle (Acacia decora)	Chenopodium auricomiforme
		Poison Pimelea (Pimelea neo-anglica)	Hoary Guinea Flower (Hibbertia obtusifolia)
			Pinkwood (Beyeria viscosa)
			Large Tick-trefoil (Desmodium brachypodum)

Landform	Gently undulating rises	Hills	Crests and ridges
			Western Silver Wattle (Acacia decora)
			Velvet Mock Olive (Notelaea microcarpa subsp. microcarpa)
			Hopbushes (Dodonaea sinuolata subsp. sinuolata
			Dodonaea viscosa subsp. angustissima)
			Shiny-leaved Canthium (Psydrax odorata)
			Poison Pimelea (Pimelea neo-anglica)
Ground covers	Purple Wire-grass (Aristida personata)	Wallaby Grass (Austrodanthonia fulva)	Bristly Cloak Fern (*Cheilanthes distans*)
	Wallaby Grass (Austrodanthonia fulva)	Wallaby Grass (Austrodanthonia racemosa var. obtusata)	Poison Rock Fern (*Cheilanthes sieberi* subsp. *sieberi*)
	Slender Bamboo Grass (Austrostipa verticillata)	Speargrass (Austrostipa scabra subsp. scabra)	Blue Trumpet (*Brunoniella australis*)
	Knottybutt Grass (Paspalidium constrictum)	Barbwire Grass (Cymbopogon refractus)	Pink Tongues (*Rostellularia adscendens* var. *adscendens*)
	Tall Chloris (Chloris ventricosa)	Slender Bottle-washers (Enneapogon gracilis)	Native Carrot (*Daucus glochidiatus* form F)
	Speargrass (Austrostipa scabra subsp. scabra)	Bristly Cloak Fern (Cheilanthes distans)	Purple Burr-daisy (*Calotis cuneifolia*)
	Curly Windmill Grass (Enteropogon ramosus),	Poison Rock Fern (Cheilanthes sieberi subsp. sieberi)	Yellow Burr-daisy (*Calotis lappulacea*)
	Granite Lovegrass (Eragrostis alveiformis)	Blue Trumpet (Brunoniella australis)	Common Everlasting (*Chrysocephalum apiculatum*)
	Snowgrass (Poa sieberiana var. sieberiana)	Pink Tongues (Rostellularia adscendens var. adscendens)	Yellow Buttons (*Chrysocephalum semipapposum*)
	Queensland Bluegrass (Dichanthium sericeum)	Native Carrot (Daucus glochidiatus form F)	Cudweed (*Euchiton sphaericus*)
	Sida (Sida spinosa)	Purple Burr-daisy (Calotis cuneifolia)	Cobbler’s Tack (*Glossocardia bidens*)
	Corrugated Sida (Sida corrugata)	Yellow Burr-daisy (Calotis lappulacea)	Common Sunray (*Triptilodiscus pygmaeus*)
	Spiked Sida (Sida subspicata)	Cudweed (Euchiton sphaericus)	Fuzzweed (*Vittadinia sulcata*)
	Variable Daisy (Brachyscome ciliaris var. subintegrifolia)	Cobbler's Tack (Glossocardia bidens)	Golden Everlasting (*Xerochrysum bracteatum*)
	Hogweed (Zaleya galericulata)	Vittadinia (Vittadinia sulcata)	Bluebell species (*Wahlenbergia communis*
	Cudweed (Euchiton sphaericus)	Tufted Bluebell (Wahlenbergia communis)	Bluebell species *W. gracilenta*
	Fuzzweed (Vittadinia pustulata)	Kidney Weed (Dichondra repens)	Bluebell species *W. gracilis*
	Galvanised Burr (Sclerolaena birchii)	Large Tick-trefoil (Desmodium brachypodum)	Bluebell species *W. stricta* subsp. *alterna*)
	Blue Trumpet (Brunoniella australis)	Smooth Darling-pea (Swainsona galegifolia)	Annual Chalkwort (*Gypsophila tubulosa*)
	Berry Saltbush (Einadia hastata)	Forest Goodenia (Goodenia hederacea)	Knotweed Goosefoot (*Einadia polygonoides*)
	Native Carrot (Daucus glochidiatus form F)	Western Stackhousia (Stackhousia muricata)	Kidney Weed (*Dichondra repens*)
	Kidney Weed (Dichondra repens	Finger Rush (Juncus subsecundus)	*Evolvulus alsinoides* var. *decumbens*
	Large Tick-trefoil (Desmodium brachypodum)	Wattle Mat-rush (Lomandra filiformis subsp. filiformis)	Caustic Weed (*Chamaesyce drummondii*)
	Slender Tick-trefoil (Desmodium varians)	Many-flowered Mat-rush (Lomandra multiflora)	Smooth Darling Pea (*Swainsona galegifolia*)
	Amulla (Eremophila debilis)		Spike Centaury (*Schenkia spicata*)
	Many-flowered Mat-rush (Lomandra multiflora),		Native Geranium (*Geranium solanderi* var. *solanderi*)
	Hairy Joyweed (Alternanthera nana)		Forest Goodenia (*Goodenia hederacea*)
	Yellow Buttons (Chrysocephalum apiculatum)		Rough Raspwort (*Haloragis heterophylla*)
	Caustic Weed (Chamaesyce drummondii)		*Oncinocalyx betchei*
	Slender Flat-sedge (Cyperus gracilis)		Dwarf Skullcap (*Scutellaria humilis*)
			Corrugated Sida (*Sida corrugata*)
			Oxalis perennans
			Swamp Dock (*Rumex brownii*)
			Rough Bedstraw (*Galium gaudichaudii*)
			Solanum parvifolium
			Western Stackhousia (*Stackhousia muricata*)
			Nodding Chocolate Lily (*Dichopogon fimbriatus*)

Landform	Gently undulating rises	Hills	Crests and ridges
			Slender Flat-sedge (*Cyperus gracilis*)
			Common Fringe- sedge (*Fimbristylis dichotoma*)
			Finger Rush (*Juncus subsecundus*)
			Wattle Mat-rush (*Lomandra filiformis* subsp. *filiformis*)
			Many-flowered Mat-rush (*Lomandra multiflora*)
			Purple Wire-grass (*Aristida personata*)
			Wallaby Grass (*Austrodanthonia racemosa* var. *obtusata*)
			Speargrass (*Austrostipa scabra* subsp. *scabra*)
			Barbwire Grass (*Cymbopogon refractus*)
			Slender Bottle-washers (*Enneapogon gracilis*)
			Two-colour Panic (*Panicum simile)*
			Knottybutt Grass (*Paspalidium constrictum*).

Source: Modified catena from Border Rivers-Gwydir Catchment Management Authority 2013, p153 Nandewar Northern Complex Province and plant communities described by Bower 2011; Tabs 8-10.

Figure 8. A typical catena of woodland grading into open forest. The scale is in the order of tens of kilometres.

Table 4. Numbers of native species found in each growth form compiled from reference condition grassy woodlands.

Growth form	Woody and non-woody	Number of species	Per cent (n= 403)
Fern	Non-woody	6	1.0%
Grass	Non-woody	53	9.0%
Herb	Non-woody	326	55.3%
Climber	Non-woody	2	0.3%
Sedge/ rush	Non-woody	16	2.7%
Shrub	Woody	126	21.4%
Shrub/ Tree	Woody	23	3.9%
Grass Tree	Woody	1	0.2%
Tree	Woody	34	5.8%
Tree/ mallee	Woody	2	0.3%
Totals		589	100.0%

Derived from: (Department of the Environment, n.d.)

It should be noted that the above table has been derived from the list developed to complement the guide for listing Box Gum Grassy Woodlands and that the list is not exhaustive and not all of the species listed will occur in every patch. Additional exotic and naturalised numbers of species that are widespread and common in Box Gum Woodlands are not listed in Table 4.

The reference state for White Box - White Cypress Pine Grassy Woodland is Community 3 defined by (Bower 2011) and its landscape position is located on the lower slopes of the catena depicted in Figure 8. This figure also provides a list of the dominant species of trees, shrubs and ground cover found in two other communities that are located higher up the catena: Community 2 White Box – White Cypress Pine Shrubby Woodland and Community 1 White Cypress Pine - Narrow-leaved Ironbark Shrubby Open Forest, respectively. It is worth noting that Community 2 which is located on Crests and ridges, has the highest numbers of species of trees, shrubs and groundcovers compared to Communities 1 and 2.

Design solutions and leading practices

Quality rehabilitation practice requires knowledge of reference species composition as a starting point, but not an end point (McDonald et al 2016). A full list of indigenous overstorey species compiled from *Unmodified* condition states (Table 1) of locally occurring grassy woodlands areas should ideally define the list of species expected to have occurred on a mine site. These reference sites should be across a catena of slopes and underlying diversity of geology as illustrated in Figure 8 above. A full list of indigenous overstorey species and the relative to the number of exotic species defines the pre-mining potential species richness or diversity. As noted above, this species list is a guide, not a recipe.

If reference sites are not available due to intensive agricultural clearing, comprehensive lists of overstorey species are available from State and Territory environment departments or herbaria for grassy woodlands. These lists may or may not include exotic and naturalised species e.g. (Department of the Environment, n.d.). Such sources may be used to provide a global list before commencing mining. Alternatively, species lists for a given location can be downloaded from the Atlas of Living Australia (http://www.ala.org.au/species-by-location/).

Caution should be made in choosing and interpreting reference sites. Century long agricultural use such as grazing and selective tree harvesting and the absence of fire, may lead to unknown changes in the density and composition of species functional groups in the remaining stand. The remaining species may in fact reflect a depauperate plant community. For example, an acacia midstorey may be absent due to prolonged suppression of fire and continuous grazing.

Once a list of overstorey species has been developed that are likely to be most suited to final landforms and constructed regoliths, the provenance, or source location should be considered. Seed from local populations of the desired tree species should be sourced, but only if the seed comes from populations with at least 100 healthy individuals to ensure local genetic variation (avoid inbreeding). Additional guidance in seed selection and storage is proved by the *Florabank Guidelines* (https://www.florabank.org.au/default.asp?V_DOC_ID=755).

Recent scientific modelling and experimentation suggests that the seed mix for a given tree species should also include provenances from areas that are warmer and drier in order to provide greater genetic diversity for adaptation to rapid climate change (Booth, et al., 2012); (Boshier, et al., 2015). Prober et al. (2015) provide principles and guidelines for what they term “climate-adjusted provenancing for climate-resilient ecological restoration”.

Good rehabilitation outcomes occur when clients of rehabilitation service providers plan well ahead and allow sufficient time to source, prepare and supply the diversity, quality and volume of tree species needed (Field, 2016; Whitaker, 2016). Sourcing quality seed from suppliers is likely to be an iterative process. Seed suppliers will have lists of what’s available (e.g. ‘Species List - Western Slopes & Plains NSW’ (Field, 2016), but it may not include all the species desired for rehabilitation. Care needs to be taken in selecting species from supply lists to ensure that the species needed for the project are fit for the purpose; such lists often include those species not indigenous to the local area but will grow, e.g. *Eucalyptus bicostata* (Southern blue gum) and *Grevillea robusta* (Silky oak). It is also important to ensure plant species functional groups from different strata are included in the mix of species selected (Nussbaumer, et al., 2012).

The final list of seeds to be supplied depends on a range of factors, many of which relate to project management including; budget, timeframe and regulatory requirements. Environmental factors affecting seed supply is seasonal conditions, many tree species flower and set seed intermittently rather than predictably. Other environmental factors include few remaining woodland remnants with desired species, fragmented remnants, and access constraints; collecting seed on public land requires licenses from the appropriate authority.

Services provided by leading rehabilitation practitioners include planning and implementing a seed supply plan, sourcing seedlings and remediation contractors or undertake the remediation (Carr, 2016). Mine site rehabilitation often requires more seed than can be collected from wild populations, so rehabilitation practitioners design and establish and maintain seed production areas to ensure adequate seed supplies. Collecting sites with high species richness, high viability species populations and with requisite area of plants species and that are suitable for harvesting the volumes of seed needed are highly valued by rehabilitation practitioners (Whitaker, 2016).

Rehabilitation services should not be considered a "just in time" service (Field, 2016). Rather, leading practice rehabilitation is a long term processes (life of mine) that benefits from long term planning, adaptation and relationship building. Unlike well-established mining services (e.g. infrastructure construction), rehabilitation services are still very much a cottage industry that requires sustained support from the mining industry to expand service capacity and expertise.

Implementation risks

During critical germination, establishment and development phases of rehabilitation, it is important to select the dominant structuring species found in the reference state. Numerous factors can affect the likelihood of success in establishment of the overstorey species composition including: timing rehabilitation activities to avoid hot dry seasons with low soil moisture, choosing topsoil that has been appropriately sourced from stockpiles with low levels of weediness; selecting viable sources of seeds for germinating and establishing tube stock; avoiding the incidence of wildfire during critical periods of establishment and development; and choosing the list of species to provide dominance and sub-dominance as the rehabilitation matures.

Soils that have had a history (>10 years) of intensive agricultural practices (e.g. improved pastures and/or cropping) are known to carry a heavy burden of weed seeds and are usually high in NPK fertilizers in the top 25–50 mm of the topsoil (Windsor, et al., 2000; Cole et al., 2006; Gibson-Roy & Delpratt, 2015). (Windsor, et al., 2000) found oxidized mine overburden was an effective weed free substrate as a substitute for natural topsoil because analyses of the soil chemistry of the overburden showed similar soil properties to unmodified topsoils found in grassy woodlands in the Central Tablelands of New South Wales.

In references sites, care needs to be taken not to impinge on the species composition of the overstorey and understorey. Some key factors include limiting total grazing pressure at critical seed setting periods and reducing total grazing pressure during drought periods. Implementing time-based cell grazing may provide beneficial solutions to achieve better balances in species densities and rates of germination. Also using an appropriate fire regime, particularly the timing of burns must be considered in relation to the flowering and seeding of native and exotic species. Where possible burns should be carried out after natives have seeded but before weeds flower and seed (Appendix 2).

Scalping the top 25–50 mm and removing the topsoil to remove weeds, their seeds and surplus nutrients provides another alternative to avoid reintroducing weeds during rehabilitation (Rawlings, et al., 2010). Depending on the size of the area to be scalped a road grader blade, road scraper or offset discs may be used to scalp the weedy and nutrient rich topsoil, which must be removed well away from the site or otherwise it will contaminate the topsoil dump that is intended to be used for rehabilitation.

Nussbaumer (2005) working at Mount Owen Mine showed that survival of *Eucalyptus maculata* in spoil alone was only half of that in topsoil (reference state) after four years.

Wherever available, and possible, direct-transfer forest topsoil should be used for rehabilitation, as it produces the highest native plant density and species richness (Cole et al., 2006).

Knowledge gaps and priority research

The majority of Australian woody species have associations with mycorrhizal and/or rhizobial bacteria associations and woody species can be harder to establish and lower survival where these microbial associations are absent or greatly diminished (Warcup 1980, Carrenho et al. 2008, Thrall et. al. 2011). There is now significant evidence that these symbiotic associations are greatly diminished by top soil stripping, with or without stockpiling (reviewed above). What is less well known is how rapidly these symbionts recolonise rehabilitated mine sites, likely via wind dispersed spores. The hypothesis is that soil symbionts colonise host plant roots within a few years, but inoculation of seedlings at time of planting may enhance early survival.

Eucalypts of grassy woodlands are keystone or framework species and can live for over 200 years in some instances. The climate in 200 years from now is likely to be quite different to current conditions. More research is needed on how to select genetic seed provenances that have the greatest adaptive capacity to rapidly changing climate.

Field trials to improve efficiency of establishment and growth are provided above under other Ecological Criteria.

10. Understorey composition

Ecological criterion definition and attributes

Species composition (e.g. richness) and functional group identity are the key quantifiable components of understorey attributes.

Understorey species functional groups include: perennial herbs, monocots, introduced perennial herbs, grass-like monocots, annual herbs, introduced grass-like monocots, introduced annual herbs and ferns (Cummings & Reid, 2008). The diversity of cryptogamic crusts found in grassy woodlands (over 50 found in one small district, Eldridge et al. 2006) should also be included in understorey composition.

Land use and management practices maintain or modify the number and densities of understorey species functional groups. Changes made to species functional groups generally reflect the values of a land manager and of the wider society. Depending on a land manager's goal/purpose for managing a site, various mixes and densities of these functional groups of the native vegetation are maintained, modified, removed and/or replaced.

(Hnatiuk, et al., 2009a) describes common methods to quantitatively describe understorey composition.

Problem definition

As noted in the previous section, approximately 70% of the species richness (n=403) of *Unmodified* grassy woodlands are non-woody species; and of this total over 55% are herbs, 9% are grasses (Department of the Environment, n.d.). This diversity is an awesome challenge for the rehabilitation of grassy woodlands on mined surfaces. No one reference site will have all 403 species of understorey, but any one particular reference site could potentially have over a hundred understorey species across a few hectares. The ecological restoration of this remarkable diversity on degraded (*Transformed*, Table 1) sites is at its infancy, never mind reinstating at least a portion of this diversity for mine rehabilitation.

It should be noted that this list of 403 species (Table 4) represents a comprehensive, but not exhaustive, list of understorey species developed as a guide for listing Box Gum Grassy Woodlands throughout the extent or range of this vegetation type. Perhaps the numbers of understorey species described at the regional and local levels represent a more realistic of the number of species which represent a realistic benchmark for the Whitehaven Coal Project. At a regional level the NSW Biometric Benchmark for the Namoi Grassy White Box Woodlands only lists 23 species understorey species (Department of Environment, Climate Change and Water, NSW, 2010). Similarly, at a level, Bower (2011) only lists 30 understorey species for the Tarrawonga Coal Project (Figure 8).

Reference state

It is highly valuable to find local reference sites that are at least classed as *Transformed* (Table 2). The knowledge gained from reference sites is fundamental to the rehabilitation planning, implementation and evaluation process (SERA 2016). A full list of indigenous understorey species and the relative to the number of exotic species defines the potential pre-mining species richness or diversity. The location of potential reference sites can be gained from the Atlas of Living Australia (http://www.ala.org.au/species-by-location/). It is understood that Maules Creek Coal Mine has selected and surveyed reference sites; these sites should be included as an Appendix to the next version of this report and evaluated to confirm their appropriateness as reference sites.

A complementary strategy for determining potential species composition of local reference conditions can be obtained by viewing comprehensive lists of understorey species that are available from State and Territory environment departments or herbaria for grassy woodlands. These lists may or may not include exotic and naturalised species, e.g. (Department of the Environment, n.d.) Such lists may be used to provide a global list before commencing mining.

In general, in *Unmodified* and *Modified* classes (Table 1) extents of Grassy Box Woodlands the groundlayer is usually dominated or co-dominated by one or more species of grass such as Kangaroo Grass (*Themeda triandra*, known in NSW as *T. australis*), Snow Grass (*Poa sieberiana*) and/or River Tussock (*P. labillardieri*). A herb-rich groundlayer of forbs and other grasses include; Wiregrasses (*Aristida* spp.), Vanilla Lilies (*Arthropodium* spp.), Common Woodruff (*Asperula conferta*), Wallaby Grasses (*Austrodanthonia* spp.), Speargrasses (*Austrostipa* spp.), Weeping Grass (*Microlaena stipoides*), Bulbine Lily (*Bulbine bulbosa*), Redgrasses (*Bothriochloa* spp.), Tick-trefoils (*Desmodium brachypodum* and *D. varians*), Bluegrasses (*Dichanthium* spp.), Rock Fern (*Cheilanthes sieberi* ssp. *sieberi*), Common Everlasting (*Chrysocephalum apiculatum*), Flax Lilies (*Dianella* spp.), Nodding Chocolate Lily (*Dichopogon fimbriatus*), Common Wheat Grass (*Elymus scaber*), Native Geraniums (*Geranium retrorsum* and *G. solanderi*), Native Soyas (*Glycine clandestina* and *G. tabacina*), Scrambled Eggs (*Goodenia pinnatifida*), Small St John's Wort (*Hypericum gramineum*), Red-anthered Wallaby Grass (*Joycea pallida*), Scaly Buttons (*Leptorhynchos squamatus*), Native Flax (*Linum marginale*), Mat-rushes (*Lomandra* spp.), Yam Daisy (*Microseris lanceolata*), Grassland Wood Sorrel (*Oxalis perennans*), Native Sorghum (*Sorghum leiocladum*) and Creamy Candles (*Stackhousia monogyna*) (Keith, 2004); (Department of Environment and Conservation, 2005).

As land management becomes even more intensive grassy woodland understorey becomes increasingly modified; native grasses are replaced by annual and perennial exotic species. A number of native forb species can withstand and/or benefit from some disturbance, but a suite of native forbs are lost early in the degradation process. As the effects of land management increase, typically as a result of grazing pressure, only a few species of ground flora persist in highly degraded remnants (Moore, 1953) (Moore, 1970) (Prober & Thiele, 1993). In highly degraded remnants (i.e. the *Transformed* class (Table 1), a sparse shrub layer may be present comprising wattles (*Acacia* spp.), Native Blackthorn (*Bursaria spinosa*), Native Olive (*Notelaea microcarpa*) and pea shrubs including as *Eutaxia*, *Dillwynia* and *Templetonia* (Department of Environment, Climate Change and Water, NSW, 2010).

Design solutions and leading practices

The first and most likely important practice is to apply 'native' topsoil with reference condition levels of plant nutrients and low levels of weeds in the soil seedbank. The use of stabilised (e.g. gypsum) subsoils may be more effective for native ground cover rehabilitation than using agricultural soils that are likely nutrient enriched and contaminated with large reserves of weed seeds (http://www.tomfarrellinstitute.org/). Native soils are a high value resource for rehabilitation and should at no time be contaminated (mixed) with agricultural soil.

Assuming there is an inadequate soil seed bank, a priority list of species needs to be selected for sowing. Eucalypts are keystone overstorey species, large tussock grasses are keystone understorey species. When developing a list of priority grasses, it is important to build the functional diversity for a site by making sure that the grass seed mix comprises a range of species that are able to take advantage of the immediate seasonal conditions whether they are wet or dry, hot or cold (Whitaker, 2016). This is done by including in the seed mix, locally native grass species which germinate in different season, e.g. spring and autumn. The rationale is the seed will persist in the soil until the seasonal conditions favour a particular species, and functional different grasses take advantage of the seasonal rainfall that characterises temperate grassy woodlands (Whitaker, 2016). Huxtable (1999) five species of native perennial grass suitable for mine rehabilitation in the Hunter Valley of namely, Wallaby Grass and Plains Grass (cool season active), while the best warm season species were Queensland Bluegrass, Windmill Grass and native Couch.

The geographical origin of selected species should also be considered. A "climate-adjusted provenancing" seed sourcing strategy has been advocated by Prober et al. (2015) and others. This includes sourcing local provenances as well as provenances from warmer and drier climates within the climatic range of each ground cover species. This approach has been tested experimentally by Hancock and Hughes (2014). They found that provenances of kangaroo grass (*Themeda australis*) grown from warmer climates during a hot summer in the Sydney basin demonstrated comparable, often better growth performance than local provenance plants. This research was extended to other understorey species namely *Bursaria spinosa* and *Hardenbergia violacea*. They found little evidence that local provenances were superior to distant provenances in terms of survival and establishment (Hancock et al., 2012).

Unlike the small quantity of seed needed to propagate tree seedlings in a nursery, large quantities of understorey seed are needed for mine rehabilitation. Unlike exotic pasture species, hundreds of kilos cannot be ordered and delivered with a week's notice. Rather a long term seed supply needs to be developed to match the scale (hundreds of hectares) and duration of rehabilitation (decades). Few rehabilitation practitioners maintain high species rich repositories with large volumes of seed indigenous to the region (Field, 2016). Rather, once a rehabilitation project is tendered or agreed, practitioners in consultation with rehabilitation clients determine what indigenous understorey and groundcover species are fit for purpose or required and desired for a project. Practitioners then seek expressions of interest from a regional network of seed collectors, seed collections and nurseries to fill a specified order.

Care needs to be taken in selecting species from seed supplier lists to ensure that the species needed for the project are fit for the purpose; such lists may include those species not indigenous to the local area but will grow. In the case of understorey species a full range of functional groups should be reinstated (i.e. grasses, forbs, climbers and sedges) but establishing such a diversity of functional groups is still an emerging field of practice.

Native ground covers may not establish fast enough to provide herbaceous cover to protect soil recently placed on final landforms. An exotic cover crop may need to be sown. For example, establishment trials associated with road construction, i.e. exposed soil on new road verges, cuts and fills have identified problems with sowing *Austrodanthonia* (a C3 grass genus, a native grass). They found that this species generally took at least 18 months to reach maturity. Similarly *Danthonia* species tolerate low-nutrient soils, but were slow to establish and develop hence were not suitable for early slope stabilisation.

A cover crop of sterile rye-corn, was tested to see if it would develop a rapid cover particularly in cold weather and on steeper or easily-erodible slopes (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008). However rye corn sown during cold weather was not usually effective in producing the rapid growth that is necessary to protect the exposed soil during winter rains. It was found that during cold winter months forage varieties of oats produce significantly more vigorous growth than rye-corn.

An alternative to *Austrodanthonia* as to sow a cover crop of oats with *Chloris truncate*, a quicker growing C^4 native grass. When oats was sown at 100kg/ha, this crop provided a substantial root system with a very leafy cover that provides effective erosion control and assists in the suppression of weeds (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008). The oats were then sprayed out in September, well before they seeded. In response to warmer weather in October and November *Chloris* germinated producing seed as a mature plant by the end of December.

Cover crops may be sown using a paper hydro-mulch (with the aim of to providing the optimum cover needed for the seed) with the addition of chemical and/or organic fertilizers to temporarily overcome the soil’s nutrient deficiency and support the growth of the cover crop (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008). However, this risks enhancing soil nutrients for weeds.

Another cover crop alternative for south and east facing slopes is to hydroseed *Microlaena stipoides* (a C^3 grass) in conjunction with the oats due to the later germination of *Microlaena*; noting that the oats must be sprayed out before October (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008).

Chloris and *Enneapogon* (C^4 native grasses) are considered to be best suited for sowing on north to west facing slopes or exposed sites. Like most other Australian native grasses, these grasses are adapted to low nitrogen soils. It is important to note that these species should be sown without a mulch, which could inhibit close contact of the seed with the ground (Government of South Australia, Department of Planning, Transport and Infrastructure, 2008).

An alternative or complement to sowing a cover crop is to apply mulch. Essential weed free rice straw has proven successful for leading rehabilitation practitioners in southern NSW (Whitaker, 2016; McPhee 2013). For large areas, rice straw was applied by a commercial forced air spreader designed for piggeries (Whitaker, 2016). Rice straw is particularly effective at 'sticking' to soil surfaces and protects directly sown seeds from seed predators and erosion.

A cover crop of fertile exotic grasses and sorghum should not be planted on a topsoil mound which has a high integrity for native vegetation. This is likely to contaminate the mound and the future soil that will be used for re-establishing native vegetation (Field, 2016)

Implementation risks

There are three key risks: failure to sow and establish a diversity of native ground cover species, the risk of competition from weeds, and the risk of being shaded out by an overstorey that is planted too densely (e.g. Figure 6). Risk management strategy for the first risk is to develop a long term seed supply strategy in collaboration with leading service providers. For the second risk, use 'native' weed free topsoils where ever possible. For the third risk, hand plant trees at a density of 50 stems/ha or less.

In addition, in the early phases of rehabilitation of grassy woodlands, particular care will be required to limit total grazing pressure at critical flowering and seeding periods for ground cover species and reducing total grazing pressure during drought periods. Implementing an appropriate fire regime, particularly the timing of burns may need to be considered in relation to the flowering and seeding of native and exotic species as reviewed under Criterion 5(Disturbance Regime). Where possible burns should be carried out after native species have seeded but before weeds flower and seed.

In references sites, care needs to be taken not to impinge on the functional characteristics of the understorey. Some key factors that need to be considered include limiting total grazing pressure at critical flowering and seeding periods for ground cover species and reducing total grazing pressure during drought periods. Implementing time-based cell grazing may provide beneficial solutions to achieve better balances in densities of tussock grasses and forbs. Also using an appropriate fire regime, particularly the timing of burns must be considered in relation to the flowering and seeding of native and exotic species. Where possible burns should be carried out after the framework species have seeded but before weeds flower and seed (Appendix 2).

Cole et al., (2006) tested a number of topsoils, ranging from disturbed, stockpiled, Ravensworth State Forest and pasture topsoil at Mount Owen, to freshly transferred woodland and pasture topsoil at Warkworth. These authors concluded that not all topsoils are equally useful in recreating native plant density and species richness. They found that stockpiled forest topsoil, contributed 28 native species to the rehabilitation area. In an earlier study Nussbaumer (2005) found that forest topsoil at Mount Owen Mine, contributed 78 native plant species to the rehabilitation area.

Wherever available, and possible, direct-transfer forest topsoil should be used for rehabilitation, as it produces the highest native plant density and species richness (Cole et al., 2006).

Pasture topsoil with large weed and grass seed banks should not be used for native forest and woodland reconstruction, using seeding, without amelioration to combat the weeds (Cole et al., 2006).

Knowledge gaps and priority research

There is a priority need to develop cost effective strategies and technologies to enhance ground flora diversity and cover/abundance. As described above under Criterion 4, research is needed to understand what diversity of native vs exotic flora can survive both soil stripping and soil stockpiling. The hypothesis is that a low cost and floristically diverse strategy is to direct transfer of topsoil stripped from native grassy woodlands.

The lack of reliable and large seed supplies of a diversity of ground cover species is a major constraint to rehabilitation. Field trials are needed to examine the effectiveness of enhancing remnants of grassy woodlands to produce a larger diversity and abundance of native ground covers that can be harvested for mine rehabilitation. Field trials are also needed to examine the most cost and ecologically effective means of sowing a diversity of ground flora.

As described under Criterion 5, research into the effect of various exotic covers crops on suppressing or enhancing native flora establishment is also needed.

Recommendations

This review has identified the following knowledge gaps and uncertainties in grassy woodland rehabilitation that require further investigation.

Function

1. It is hypothesised that where capping is used[2], deep ripping of capping materials facilitates root access to the regolith, but this has not been demonstrated experimentally. It is also hypothesised that, in general eucalypt woodland tree species can utilise constructed regoliths and their roots may help reduce the risk of sub-soil erosion (e.g. tunnelling)[3].

2. Research trials are warranted to investigate the value of mounding compared to just ripping. Trials should also be conducted on the functional value (e.g. rainfall infiltration and tree survival) of spacing between mounds. The longevity of these mounds should be monitored

[2] It should be noted that not all of the overburden emplacement is capped as standard practice. Only adverse spoil/materials are capped. If possible, weathered overburden is dumped preferentially near to the final landform surface but this is often not practicable due to scheduling/sequencing of mining (Andrew Wright pers comm)

[3] Conversely roots may also provide the pathway to the dispersive subsoil and exacerbate tunnelling (Andrew Wright pers comm)

as well.

3. The costs and benefits of ‘double gypsum’ treatment of soil and regolith requires further investigation.

4. The effect of topsoil stripping and stockpiling on infiltration and water holding capacity, and rapid ways to improve these fundamental functions requires investigation.

5. Field trials of tightly targeted application of fertiliser to enhance seedling establishment and survival should be conducted if poor seedling survival is shown to be a significant risk and if lab analysis shows low soil nutrient status well below reference levels.

6. If agricultural soils have to be used for grassy woodland rehabilitation, trials should be conducted to see if excess nutrients can be stripped from such soils by the repeated establishments and harvesting of cover crops with high nutrient uptake potential.

7. Field trials to test the effect of spreading freshly stripped, compared to stockpiled topsoils, is warranted as long as the fresh and stockpiled soils had similar pre-mining properties (e.g. both came from formally wooded or forested soil landscapes).

8. Trials of commercially available fungal and rhizobial inoculants should be tested on both freshly stripped native soils and stockpiled soils. We hypothesise that inoculants will be most beneficial in stockpiled soils.

9. We found only limited research is available on how the native soil seedbank stripped from forests and woodlands in eastern Australian is affected by stockpiling. Nussbaumer, et al., (2012) found that almost half of the native species found in the rehabilitation site for Mount Owen Coal Mine which survived in stockpiled forest topsoil and associated seed bank. These authors notes that the source of this topsoil came from a site a dry sclerophyll forest that was previously logged and grazed. The Keipert et al. (2004) study focussed on the soil seed bank of agricultural topsoils stockpiled in the Hunter Valley. We predict that viable eucalypt seeds will quickly be lost from stockpiles, but hard seeded acacias may survive, even at depth, particularly if the stockpiles are kept relatively dry.

10. Further research into the role of fire to enhance the diversity and persistence of grassy woodlands need to continue, but at this point in time, this is most relevant to the management of remnants of grassy woodland, for instance those found in offset areas established by the mining industry. In the fullness of time, the role of fire based on research on remnants can be applied to rehabilitated mine sites when operations and infrastructure are removed at closure.

11. Research that can begin at the time of rehabilitation plantings should examine the natural reproductive potential of short lived species, particularly ground cover grasses and herbs. The hypothesis is that the herbaceous understorey can self-regenerate in a matter of a few

years depending on seasonal conditions, lack of weeds and low grazing pressure.

Structure

12. Field trials are needed to examine planting designs and technologies. The environmental benefits of combining hand planting of a low density of eucalypts with direct seeding needs to be investigated.

13. We hypothesise that it may take at least 10 years or more for artificially place fallen timber to be colonised by at least some common species of wildlife. It is also worth setting up a field trial to investigate the effects of two contrasting strategies to distribute equal volumes of fallen timber – clumps vs scattered. A similar study of placing clumps or a scatter of inert rock should be conducted on those mines with such rocks.

Composition

14. Research is needed on how these traditional cover crops negatively or positively affect the establishment of native grassy ground covers. Alternative organic covers should also be investigated such as native hays or rice straw that is very low in terrestrial weed seeds and has been shown to effectively 'stick'[4] on recently placed topsoils (Figure 4).

15. There is a priority need to develop cost effective strategies and technologies to enhance ground flora diversity and cover/abundance.

16. The lack of reliable and large seed supplies of a diversity of ground cover species is a major constraint to rehabilitation. Field trials are needed to examine the effectiveness of enhancing remnants of grassy woodlands to produce a larger diversity and abundance of native ground covers that can be harvested for mine rehabilitation. Field trials are also needed to examine the most cost and ecologically effective means of sowing a diversity of ground flora.
17. Greater than half of Australian woody species have a dependency on mycorrhizal or rhizobial bacteria associations and woody species can be harder to establish and lower survival where these microbial associations are absent or greatly diminished. What is less well known is how rapidly these symbionts recolonise rehabilitated mine sites, likely via wind dispersed spores. The hypothesis is that soil symbionts colonise host plant roots within a few years, but inoculation of seedlings at time of planting may enhance early survival.

18. Eucalypts of grassy woodlands are keystone or framework species and can live for over 200 years in some instances. The climate in 200 years from now is likely to be quite different to current conditions. More research is needed on how to select genetic seed provenances that have the greatest adaptive capacity to rapidly changing climate.

[4] Evidence from Owen Whittaker's rehabilitation practices in the Canberra region.

Recommended implementation and review

These 18 key knowledge gaps identified by this review process need to be prioritised as it is unlikely there are sufficient resources to conduct research on each gap. It is beyond the scope of this review to provide such a prioritisation. We are aware of the *Maules Creek Coal Mine Box-Gum Woodland Research Project Plan* (2015), but a review of this *Plan* is outside the scope of this structured literature review.

However, transforming sites and landscapes towards a reference state relies on: ecological literacy, setting clear goals; purposeful decisions; experiments and treatments; monitoring, reporting evaluation and improvement; knowledge transfer; and implementation at broader scales (Lawrence, et al., 2007) (Gibson-Roy & Delpratt, 2015). We recommend this adaptive research process be used to review and modify the 2015 *Research Project Plan.*

Key to understanding which ecological processes have been degraded or transformed and to restoring these ecological processes is to use a systems approach and to define a core set of criteria and indicators as we have done here. This framework provides a robust system for explaining the theory and leading practice for mine rehabilitation to re-establish grassy box woodlands over time. Successful mine site rehabilitation addresses the restoration of all three components of vegetation condition; function, structure and composition informed by a core set of criteria and indicators measured relative to a well-researched natural reference state.

Where a fully natural ecosystem is the goal of management, it is necessary to determine which criteria have been modified and to what extent compared to a fully natural reference state. That information is then used to inform land managers as to what inputs or interventions may be used to enhance or restore particular functions. Where little is known of how to restore the functions of particular ecosystems, replicated field experiments or trials are a valuable tool for learning on the job as recommended below. A commitment to monitoring and management of the reference site(s) and the rehabilitation site are fundamental to achieving long-term successful outcomes that approximate the reference state.

We recommend that a skills based research steering committee be established to review the *Research Project Plan* in light of this literature review and the 18 key knowledge gaps we have identified. We recommend that the membership of the steering committee include at least one senior environmental manager from Whitehaven Coal, at least one independent senior consultant with extensive experience in coal mine rehabilitation and at least one senior academic with extensive experience in mine rehabilitation and ecological restoration research. Recommended tasks of this steering committee are:

1. Prioritise research on the knowledge gaps identified by this literature review. It is critically important that Whitehaven Coal is fully involved in this prioritisation process to ensure that the rehabilitation research is well targeted to meeting their needs in effectively restoring grassy woodlands to Maules Creek mined surfaces.

2. Provide oversight of the research program contracted by Whitehaven Coal. Such a committee can play a valuable role in ensuring that research projects are well designed, implemented, appropriately analysed and results effectively communicated.

3. Regularly review the on-going research plan to ensure that the research is adaptive. That is, as research results are delivered, they need to be effectively used to inform existing and new research funded by Whitehaven.

4. Assist Whitehaven to interpret research results and apply research outcomes to on-going rehabilitation of grassy woodlands at Maules Creek.

5. Finally, we recommend that a dedicated field based researcher be selected by this steering committee to lead the implementation, monitoring, analysis and reporting of research integrated into rehabilitation activities at Maules Creek. Such a person is needed to be on site at critical times to leverage the resources expended on rehabilitation into an appropriate experimental design (e.g. treatments and controls). Such rehabilitation trials need regular monitoring that is well beyond the scope of mine site rehabilitation staff with numerous other demanding responsibilities. Members of this steering committee can also play a role in providing strategic advice and mentorship to the field based researcher.

References

ALCOA Australia, n.d.. *Pre-ripping.* [Online]
Available at: http://www.alcoa.com/australia/en/info_page/mining_pre_ripping.asp
[Accessed 26 April 2016].

Andersen, A. N., Hoffmann, B. D. & Somes, J., 2003. Ants as indicators of minesite restoration: community recovery at one of eight rehabilitation sites in central Queensland. *Ecological Management & Restoration,* Volume 4, pp. S12-S19.

Auscover Remote Sensing Data facility, Queensland Department of Science, Information Technology and Innovation, 2015. *Annual Fire Scars - Landsat, QLD DSITIA algorithm, QLD coverage.* [Online]
Available at:
http://www.auscover.org.au/xwiki/bin/view/Product+pages/Landsat+fire+scars+Queensland
[Accessed 28 April 2016].

Austin, M. et al., 2002. *Predicted Vegetation Cover in Central Lachlan Region. Final Report of the Natural Heritage Trust Project AA 1368.97,* Canberra: CSIRO Wildlife and Ecology.

Australian and New Zealand Minerals and Energy Council (ANZMEC) & Minerals Council of Australia (MCA), 2000. *Strategic Framework for Mine Closure.* [Online]
Available at:
http://www.sernageomin.cl/pdf/mineria/cierrefaena/DocumentosRelacionados/Strategic-Framework-Mine-Closure
[Accessed 2 April 2016].

Australian Bureau of Agricultural and Resource Economics and Sciences, 2011. *Guidelines for land use mapping in Australia: principles, procedures and definitions, fourth edition,* Canberra: Australian Bureau of Agricultural and Resource Economics and Sciences.

Australian Government, Department of the Environment, n.d.. *White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland National Recovery Plan.* [Online]
Available at: https://www.environment.gov.au/resource/white-box-yellow-box-blakelys-red-gum-grassy-woodland-and-derived-native-grassland-national
[Accessed 28 April 2016].

Australian Government, 2016. *Pacific climate change science climate futures - Understanding climate variability and change.* [Online]
Available at: http://www.pacificclimatefutures.net/en/help/climate-projections/understanding-climate-variability-and-change/
[Accessed 2 May 2016].

Barrett, D. et al., 2011. *Quantitative Approach To Improving The Business Of Biodiversity Investment,* Brisbane: Australian Coal Association Research Program Project Number: C17030.

Beadle, N., 1981. *The Vegetation of Australia.* Cambridge: Cambridge University Press.

Bell, D. T. & Williams, J. E., 1997. Eucalypt ecophysiology. In: J. E. Williams & J. C. Z. Woinarski, eds. *Eucalypt ecology: Individuals to ecosystems.* Cambridge: Cambridge University Press, pp. 168-196.

Bell, L. C., 2001 . Establishment of native ecosystems after mining — Australian experience across diverse biogeographic zones. *Ecological Engineering,* Volume 17, p. 179–186.

Biswas, S. & Gawade, B. H., 2016. *Role of belowground organisms in maintaining soil health.* [Online] Available at: http://www.biotecharticles.com/Agriculture-Article/Role-of-Belowground-Organisms-in-Maintaining-Soil-Health-3501.html
[Accessed 26 April 2016].

Booth, T., Williams, K. & Belbin, L., 2012. Developing biodiverse plantings suitable for changing climatic conditions 2: Using the Atlas of Living Australia. *Ecological Management and Restoration,* pp. 13: 274-281.

Border Rivers-Gwydir Catchment Management Authority, 2013. Vegetation Profiles. In: W. Miller, et al. eds. *Managing and Conserving Native Vegetation, Information for land managers in the Border Rivers-Gwydir catchments, Parts 1-4.* Inverell: Border Rivers-Gwydir Catchment Management Authority.

Boshier, D. et al., 2015. Is local best? Examining the evidence for local adaptation in trees and its scale. *Environmental Evidence,* 4(20), pp. 1-10.

Bower, C. C., 2011. *Tarrawonga Coal Project, Environmental Assessment, Flora Assessment, Appendix F,* Gunnedah: Whitehaven Coal.

Bradstock, R. A., Williams, J. E. & Gill, A. M. eds., 2002. *Flammable Australia. The Fire Regimes and Biodiversity of a Continent.* Melbourne: Cambridge University Press.

Breed, M. F., Gellie, N. J. & Lowe, A. J., 2016. Height differences in two eucalypt provenances with contrasting levels of aridity. *Restoration Ecology,* pp. 1-8.

Breed, M. F. et al., 2013. Which provenance and where? Seed sourcing strategies for revegetation in a changing environment. *Conserv Genet,* Volume 14, p. 1–10.

Broadhurst , L. M., 2013. A genetic analysis of scattered Yellow Box trees (Eucalyptus melliodora A.Cunn. ex Schauer, Myrtaceae) and their restored cohorts. *Biological Conservation,* Volume 161 , p. 48–57.

Brundrett, M. C. & Abbott, L. K., 1991. Roots of jarrah forest plants. I. Mycorrhizal associations of shrubs and herbaceous plants.. *Australian Journal of Botany,* Volume 39, pp. 445-457.

Buckney, R. T. & Morrison, D. A., 1992. Temporal trends in plant species composition on mined sand dunes in Myall Lakes National Park, Australia. *Australian Journal of Ecology,* Volume 17, pp. 241-254.

Burger, J. A., 2015. Mined land reclamation in the Apalachian coalfields: a case for an ecosystem reclamation approach. In: M. Tibbett, ed. *Mining in ecologically sensitive landscapes.* Clayton South: CSIRO Publishing, pp. 7-27.

Burges, A., 1958. *Microorganisms in the Soil.* s.l.:Hutchinson.

Burk, L. & Dalgliesh, N., 2008. *Estimating plant available water capacity-a methodology,* Canberra: CSIRO Sustainable Ecosystems.

Carr, D., 2016. *Ecological Consultant at Stringybark Ecological and owner and director of Stringybark Ecological* [Interview] (19 April 2016).

Correnho, R., Barbosa, F.F., Araujo, C.V.M., Alves, L.J., Santos, O.M. 2008. Mycorrhizal associations in eucalyptus spp.: status and needs. *Tree and Forestry Science and Biotechnology* 2, 57-67.

Cole, M., Nussbaumer, Y., Castor, C. & Fisher, N., 2006. *Topsoil substitutes and sustainability of reconstructed native forest in the Hunter Valley,* Brisbane: Australian Coal Associates Reseearch Program, Project C12033.

Collins, M. & Brundrett, M., 2015. Recovery of terrestrial orchids in natural ecosystems after severe disturbance. In: M. Tibbett, ed. *Mining in ecologically sensitive landscapes.* Clayton South: CSIRO Publishing, pp. 142-58.

Colloff, M. J., Pullen, K. R. & Cunningham, S. A., 2010 . Restoration of an Ecosystem Function to Revegetation Communities: The Role of Invertebrate Macropores in Enhancing Soil Water Infiltration. *Restoration Ecology,* 18(1), p. 65–72.

Cummings, J. & Reid, N., 2008. *Biodiversity Conservation,* Volume 17, p. 1187–1211.

Damian, R. M. et al., 2015. Ecological niche breadth and microhabitat guild structure in temperate Australian reptiles: Implications for natural resource management in endangered grassy woodland ecosystems. *Austral Ecology,* Volume 40, p. 651–660.

Daynes, C., 2012. *Soil restoration PhD Thesis.,* s.l.: School of Biological Sciences: The University of Sydney.

Department of Environment and Conservation, 2005. *Box-Gum Grassy Woodland and Derived Native Grassland – profile,* Sydney: Department of Environment and Conservation, NSW.

Department of Environment, Climate Change and Water, NSW, 2010. *National Recovery Plan for White Box - Yellow Box - Blakely's Red Gum Grassy Woodland and Derived Native Grassland,* Sydney: Department of Environment, Climate Change and Water, NSW.

Department of Industry, Tourism and Resources (DITR), 2006a. *Mine Closure and Completion - Leading Practice Sustainable Development Program for the Mining Industry.* [Online]
Available at: http://www.industry.gov.au/resource/Documents/LPSDP/LPSDP-MineClosureCompletionHandbook.pdf
[Accessed 5 April 2016].

Department of Industry, Tourism and Resources (DITR), 2006b. *Mine Rehabilitation - Leading Practice Sustainable Development Program for the Mining Industry.* [Online]
Available at:
http://www.minerals.org.au/file_upload/files/resources/enduring_value/mine_rehab.pdf
[Accessed 5 April 2016].

Department of Sustainability and the Environment, 2005. *Grassy Woodland Threatened in the Goulburn Broken Catchment,* Melbourne: Department of Sustainability and the Environment.

Department of the Environment, n.d. *White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Ecological Community Species List.* [Online]
Available at: http://www.environment.gov.au/system/files/resources/be2ff840-7e59-48b0-9eb5-4ad003d01481/files/box-gum-species.pdf
[Accessed 4 May 2016].

Department of Trade and Investment Regional Infrastructure and Services, 2013. *Guidelines to the Mining, Rehabilitation & Environmental Management Process.* [Online]
Available at:
http://www.resourcesandenergy.nsw.gov.au/__data/assets/pdf_file/0009/475434/ESG3-Mining-Operations-Plan-MOP-Guidelines-September-2013.pdf
[Accessed 2 April 2016].

Doley, D. & Audet, P., 2016. What part of mining are ecosystems? Defining success for the 'restoration' of highly disturbed landscapes. In: V. R. Squires & S. Whisenant, eds. *Ecological Restoration: Global Challenges, Social Aspects and Environmental Benefits.* New York: Nova Publishers, pp. 57-88.

Dorrough, J., Ash, J. & McIntyre, S., 2004. Plant responses to livestock grazing frequency in an Australian temperate grassland. *Ecography,* Volume 27, p. 798–810.

Eddy, D., 2002. *Managing native grassland: a guide to management for conservation, production and landscape protection,* Sydney: WWF Australia.

Eldridge, D. J. & Freudenberger, D., 2005. Ecosystem wicks: Woodland trees enhance water infiltration in a fragmented agricultural landscape in eastern Australia. *Austral Ecology,* Volume 30, p. 336–347.

Eldridge, D. J., Freudenberger, D. & Koen , T. B., 2006. Diversity and Abundance of Biological Soil Crust Taxa in Relation to Fine and Coarse-scale Disturbances in a Grassy Eucalypt Woodland in Eastern Australia. *Plant and Soil ,* 281(1/2), pp. 255-68.

Fensham, R. J., Fairfax, R. J. & Buckley, Y. M., 2008. An experimental study of fire and moisture stress on the survivorship of savanna eucalypt seedlings. *Australian Journal of Botany,* Volume 56, pp. 693-697.

Field, S., 2016. *Field's tree planting services, Uralla, NSW* [Interview] (19 April 2016).

Freudenberger, D., Harvey, J. & Drew, A., 2004. Predicting biodiversity benefits of the Saltshaker Project, Boorowa, NSW. *Ecological Management and Restoration,* Volume 5, pp. 5-14.

Gardner , J. H. & Malajczuk, N., 1988. Recolonisation of Rehabilitated Bauxite Mine Sites in Western Australia by Mycorrhizal Fungi. *Forest Ecology and Management,* Volume 24, pp. 27-42.

Gardner, J. H. & Malajczuk, N., 1988. Recolonisation of rehabilitated bauxite mine sites in western Australia by mycorrhizal fungi. *Forest Ecology and Management,* 24(1), pp. 27-42.

Gibbons, P., Briggs, S. V., Murphy, D. Y. & Lindenmayer, D. B., 2010. Benchmark stem densities for forests and woodlands in south-eastern Australia under conditions of relatively little modification by humans since European settlement. *Forest Ecology and Management,* 260(12), p. 2125–2133.

Gibson-Roy, P. & Delpratt, J., 2015. The restoration of native grasslands. In: N. Williams, A. Marshall & J. Morgan, eds. *Land of sweeping plains : managing and restoring the native grasslands of south-eastern Australia.* Clayton South: CSIRO Publishing, pp. 331-388.

Gillespie, M., Murray, M.-A., Mulligan, D. & Bellairs, S., 1998. *Native Understorey Species Regeneration at NSW Coal Mines, Final Report,* s.l.: Australian Coal Association Research Program: Project Number: C4009.

Government of South Australia, Department of Planning, Transport and Infrastructure, 2008. *Native Grasses Technical Notes, Part 5 - Native Grass for New Verges, Cuts and Fills, Environment Standards and Guidelines.* [Online]
Available at: http://www.dpti.sa.gov.au/standards/environment
[Accessed 21 April 2016].

Graham, S., McGinness, H. M. & O'Connell, D. A., 2009. Effects of management techniques on the establishment of eucalypt seedlings on farmland: a review. *Agroforest Syst,* Volume 77, p. 59–81.

Grant, C. D. & Koch, J., 2007. Decommissioning Western Australia's first bauxite mine: co-evolving vegetation restoraiotn techniques and targets. *Ecol Mgmt Restor,* Volume 8, p. 92–105.

Groves, R. H., Hagon, M. W. & Ramakrishnan, P. S., 1982. Dormancy and germination of seed of eight populations of Themeda australis. *Australian Journal of Botany,* Volume 30, p. 373–386.

Hagon, M. W. & Groves, R. H., 1977. Some factors affecting the establishment of four native grasses. *Australian Journal of Experimental Agriculture and Animal Husbandry,* Volume 17, p. 90–96.

Hancock, N. & Hughes, L., 2014. Turning up the heat on the provenance debate: Testing the 'local is best' paradigm under heatwave conditions. *Austral Ecology,* Volume 39, p. 600–611.

Hancock, N., Leishman, M. R. & Hughes, L., 2013. Testing the "Local Provenance" Paradigm: A Common Garden Experiment in Cumberland Plain Woodland, Sydney, Australia. *Restoration Ecology,* Volume 21, p. 569–577.

Hannan, J. C., 1995. *Mine rehabilitation - a handbook for the coal mining industry,* Sydney: New South Wales Coal Association.

Hansen Bailey, 2013. *Continuation of Bengalla Mine, Environmental Impact Statement,* s.l.: Hansen Bailey.

Harris, J. A. & Birch, P., 1989. Soil microbial activity in opencast coal mine restorations. *Soil Use and Management,* 5(4), pp. 155-160.

Harris, J. A., Birch, P. & Short, K. C., 1989. Changes in microbial community and physio-chemical characteristics of topsoils stockpiled during opencast mining. *Soil Use and Management Journal,* 5(4), pp. 161-168.

Harris, J. A. & Hirch , P., 1987. The effects on topsoil of storage during opencast mining operations.. *Journal of the Science of Food and Agriculture,* Volume 40, pp. 220-221.

Henderson, S., 2008. *Specification of Overburden for Use as Spoil Cover,* Brisbane: Australian Coal Association Research Program Project Number: C14042.

Hnatiuk, R. J., Thackway, R. & Walker, J., 2009b. *Explanatory notes for the Vegetation field handbook, version 2. October 2009. These notes provide greater detail to support: Hnatiuk RJ, Thackway R and Walker J 2009, 'Vegetation', in The National Committee on Soil and Terrain,* Canberra: Bureau of Rural Sciences.

Hnatiuk, R., Thackway, R. & Walker, J., 2009a. Vegetation. In: N. C. f. S. a. T. Information, ed. *Australian soil and land survey: field handbook.* 3rd ed. Melbourne: CSIRO Publishing, pp. 73-125.

Hnatiuk, R., Thackway, R. & Walker, J., 2009a. Vegetation. In: The National Committee for Soil and Terrain, ed. *Australian soil and land survey: field handbook.* 3rd ed. Melbourne: CSIRO Publishing, pp. 73-125.

Hodgkinson, J., Grigorescu, M. & Alehossein , H., 2013 . *Preparing A Mine For Both Drought And Flood - A Vulnerability And Adaptive Capacity Stud,* s.l.: Australian Coal Association Research Program Project Number: C21041.

Hone, J., Drake, V. A. & Krebs, C. J., 2015. Prescriptive and empirical principles of applied ecology Environmental Reviews. *Environmental Reviews,* Volume 23, pp. 170-176.

Howard, E. J., Loch, R. J. & Vacher, C. A., 2011. Evolution of landform design concepts. *Mining Technology,* 120(2), pp. 112-117.

Huxtable , C., 1999. *Rehabilitation of Open Cut Coal Mines Using Native Grasses: Management Guidelines, Final Report, July 1999,* Brisbane : Australian Coal Association Research Program Project Number: C6004 .

Jasper, D. A., Abbott, L. K. & Robson, A. D., 1989. The Loss of VA Mycorrhizal Infectivity During Bauxite Mining May Limit the Growth of Acacia pulchella R.Br. *Australian Journal of Botany,* Volume 37, p. 33–42.

Johnston, D., 2008. *Recreating grassy eucalypt woodland Junction Reefs Gold Mine, Mandurama, NSW,* Mandurama: DnA Environmental.

Jurskis, V., 2011. Benchmarks of fallen timber and man's role in nature: Some evidence from eucalypt woodlands in southeastern Australia. *Forest Ecology and Management,* 261(11), p. 2149–2156.

Keipert, N., Grant, C., Duggin, J. & Lockwood, P., 2004. *Effect of different stockpiling procedures on topsoil characteristics in open cut coal mine rehabilitation in the Hunter Valley, New South Wales,* Brisbane: Australian Coal Association Research Program, Project Number C9029.

Keith, D., 2004. *Ocean shores to desert dunes: The native vegetation of New South Wales and the ACT,* Sydney: NSW Department of Environment and Conservation.

Kelly, G., 2008. *Application of recycled organics in mine site rehabilitation,* Sydney: Department of Environment and Climate Change NSW .

Kerle, J. A., 2005. *Collation and review of stem density data and thinning prescriptions for the vegetation communities of New South Wales July 2005.,* s.l.: Department of Environment and Conservation (NSW), Policy and Science Division .

Koch, J. M., 2015. Mining and ecological restoration in the jarrah forest of Western Australia. In: M. Tibbett, ed. *Mining in ecologically sensitive landscapes.* Clayton South: CSIRO Publishing, pp. 111-39.

Land & Water Australia, 2005. Case study 1 - Thinking outside the square at 'Winona' Colin and Jason Seis 'Winona' Gulgong, NSW. In: *Managing Native Vegetation and Biodiversity Insights, Land Water and Wool Shaping the Future. August 2005.* Canberra: s.n., pp. 3-4.

Lawrence, R., Walker, J. & Hobbs, R. eds., 2007. *Linking restoration and ecological succession.* First ed. New York: Springer.

Loch , R., 2010. *Sustainable Landscape Design for Coal Mine Rehabilitation,* Brisbane: Australian Coal Association Research Program Project Number: C18024.

MacPhee, L., 2013. *Rehabilitation field guide,* Tumut: Australian Alps Liaison Committee.

Maltby, E., 1984. Response of soil microflora to moorland reclamation for improved agriculture. *Plant and Soil,* Volume 76, pp. 183-193.

Manning, A. D., Cunningham, R. B. & Lindenmayer, D. B., 2013. Bringing forward the benefits of coarse woody debris in ecosystem recovery under different levels of grazing and vegetation density. *Biological Conservation,* Volume 157, p. 204–214.

McDonald, R. C. & Isbell, R. F., 2009. Soil profile. In: T. N. C. o. S. a. Terrain, ed. *Australian soil and land survey: field handbook.* Melbourne: CSIRO Publishing,, pp. 147-204.

McDonald, T., Jonson, J. & Dixon, K. W. eds., 2016. National Standards for the Practice of Ecological Restoration in Australia. Restoration Ecology. *Restoration Ecology,* Volume S1, pp. 1-34.

McDougall, K. L., 1989. *The re-establishment of Themeda triandra (Kangaroo Grass): implications for the restoration of grasslands, A report to National Parks and Wildlife Service. Technical Report Series No. 89,* East Melbourne: Arthur Rylah Institute for Environmental Research, National Parks and Wildlife Division, Department of Conservation, Forests and Lands.

McElhinny, C., Gibbons, P. & Brack , C., 2006. An objective and quantitative methodology for constructing an index of stand structural complexity. *Forest Ecology and Management,* Volume 235, p. 54–71.

McIntyre, S., McIvor, J. & Heard, K., 2002. *Managing and Conserving Grassy Woodlands.* Collingwood: CSIRO Publishing.

McIntyre, S. et al., 2010. Biomass and floristic patterns in the ground layer vegetation of box-gum grassy eucalypt woodland in Goorooyarroo and Mulligans Flat Nature Reserves, Australian Capital Territory. *Cunninghamia,* 11(3), pp. 319-357.

Michael, D. R., Lindenmayer, D. B. & Cunningham, R. B., 2010. Managing rock outcrops to improve biodiversity conservation in Australian agricultural landscapes. *Ecological Management & Restoration,* Volume 11, p. 43–50.

Miller, R. M., Carnes, B. A. & Moorman, T. B., 1985. Factors influencing survival of vesicular arbuscular mycorrhizal propagules during topsoil storage. *Journal of Applied Ecology,* Volume 22, pp. 259-266.

Moore, C., 1953. The vegetation of the south-eastern Riverina, New South Wales. I. The climax communities. *Australian Journal of Botany,* Volume 1, pp. 485-547.

Moore, R., 1970. South eastern temperate woodlands and grasslands. In: R. Moore, ed. *Australian Grasslands.* Canberra: Australian National University Press, pp. 169-190.

Morgan, J. W. & Lunt ID, I. D., 1988. Effects of time-since-fire on the tussock dynamics of a dominant grass (Themeda triandra) in a temperate Australian grassland. *Biological Conservation,* Volume 88, pp. 379-386.

New South Wales Department of Environment, Climate Change and Water, 2010. *National Recovery Plan for White Box - Yellow Box - Blakely's Red Gum Grassy Woodland and Derived Native Grassland,* Sydney: Department of Environment, Climate Change and Water, NSW.

Niche Environment and Heritage, 2016. *Native Vegetation Rehabilitation Monitoring 2016, Mount Thorley Warkworth and Hunter Valley Operations, Report prepared for Coal and Allied on 29 March 2016,* Parramatta: Niche Environment and Heritage.

Noss, R. F., 1990. Indicators for Monitoring Biodiversity: A Hierarchical Approach. *Conservation Biology,* 4(4), p. 355–64.

NSW Environment Protection Authority, 2014. *Private Native Forestry Code of Practice Guideline No. 4, Techniques for Measuring Stand Height.* [Online]
Available at: http://www.epa.nsw.gov.au/resources/pnf/130027standheight.pdf
[Accessed 28 April 2016].

Nussbaumer, E., Castor, C. & Cole, M., 2012. *Establishing Native Vegetation - Principles and Interim Guidelines for Spoil Placement Areas and Restoration Lands,* Newcastle: Centre for Sustainable Ecosystem Restoration, The University of Newcastle.

Nussbaumer, Y., 2005. *Rebuilding Biodiversity and Microbial Associations in native Forest Rehabilitation Following Open-cut Coal Mining,* Newcastle: The University of Newcastle.

Nussbaumer, Y. M., Castor, C. & Cole, M. A., 2012. Establishing native vegetation on the Mount Owen Mine model site. *Journal of the Australian Network for Plant Conservation,* Volume 21, pp. 6-8.

O'Bryen, E., Prober, S. M., Lunt, I. D. & Eldridge, D. J., 2009. Frequent fire promotes diversity and cover of biological soil crusts in a derived temperate grassland. *Oecologia,* Volume 159, pp. 827-838.

Office of Environment & Heritage, 2014. *Climate projections for your region, New England North West Climate change snapshot.* [Online]
Available at: http://www.climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/Climate-projections-for-your-region
[Accessed 26 May 2016].

Osanai, Y., Bougoure, D. S., Hayden , H. L. & Hovenden, M. J., 2013. Co-occurring grass species differ in their associated microbial community composition in a temperate native grassland. *Plant and Soil ,* 368(1), pp. 419-431.

Parkes, D., Newell, G. & Cheal, D., 2003. Assessing the quality of native vegetation: The 'habitat hectares' approach. *Ecological Management & Restoration,* Volume 4, p. S29–S38 .

Penman, T. D. et al., 2009. Long-term changes in understorey vegetation in the absence of wildfire in south-east dry sclerophyll forests. *Australian Journal of Botany,* Volume 57, p. 533–540.

Pickup, M. et al., 2013. Post-fire recovery of revegetated woodland communities in south-eastern Australia. *Austral Ecology,* Volume 38, p. 300–312.

Prober, S. et al., 2015. Climate-adjusted provenancing: a strategy for climate-resilient ecological restoration. *Frontiers in Ecology and Evolution,* Volume 3, pp. 1-5.

Prober, S. M. & Thiele, K. R., 2005. Restoring Australia's temperate grasslands and grassy woodlands: integrating function and diversity. *Ecological Management & Restoration,* Volume 6, pp. 16-27.

Prober, S. M., Thiele, K. R. & Lunt, I. D., 2002. Identifying ecological barriers to restoration in temperate grassy woodlands: soil changes associated with different degradation states. *Australian Journal of Botany,* Volume 50, pp. 699-712.

Prober, S. M., Thiele, K. R. & Lunt, I. D., 2007. Fire frequency regulates tussock grass composition, structure and resilience in endangered temperate woodlands. *Austral Ecology,* 32(7), pp. 808-24.

Prober, S. M., Thiele, K. R., Lunt, I. D. & Koen, T. B., 2005. Restoring ecological function in temperate grassy woodlands: manipulating soil nutrients, exotic annuals and native perennial grasses through carbon supplements and spring burns. *Journal of Applied Ecology,* Volume 42, pp. 1073-1085.

Prober, S. & Thiele, K., 1993. The ecology and genetics of remnant Grassy White Box Woodlands in relation to their conservation. *Victorian Naturalist,* Volume 110, pp. 30-36.

Rawlings, K., Freudenberger, D. & Carr, D., 2010. *A guide to managing box gum grassy woodlands,* Canberra: Department of the Environment, Water, Heritage and the Arts, 2010..

Reddell P, p. & Milnes, A. R., 1992. Mycorrhizas and Other Specialized Nutrient-Acquisition Strategies: Their Occurrence in Woodland Plants From Kakadu and Their Role in Rehabilitation of Waste Rock Dumps at a Local Uranium Mine. *Australian Journal of Botany,* Volume 40, pp. 223-242.

Roberts, A. D., Cole, A. J., Nicholas, A. P. & de Nys, R., 2015. Algal biochar enhances the re-vegetation of stockpiled mine soils with native grass. *J Environ Manage,* Volume 161, pp. 173-80.

Smallbone, L. D., Prober, S. M. & Lunt, I. D., 2007. Restoration treatments enhance early establishment of native forbs in a degraded temperate grassy woodland. *Journal of Botany,* 55(8), pp. 818-830.

Smits, J., 2008. *The effectiveness of different mulches in mine rehabilitation: short-term effects on the surface stability and the conditions for plant growth, Cowal Gold Mine, NSW,* Canberra: Australian National University.

Spain, A. V., Tibbett, M., Hinz, D. A. & Ludwig, J., 2015. The mining-restoration system and ecosystem development following bauxite mining in a biodiverse environment of the seasonally dry tropics of Australia. In: M. Tibbett, ed. *Mining in ecologically sensitive landscapes.* Clayton South: CSIRO Publishing, pp. 159-227.

Speight, J. G., 2009. Landform. In: N. C. o. S. a. Terrain, ed. *Australian soil and land survey field handbook.* 3rd ed. Melbourne: CSIRO Publishing, pp. 15-72.

Speight, J. G. & Isbell, R. F., 2009. Substrate. In: The National Committee for Soil and Terrain, ed. *Australian soil and land survey: field handbook.* Melbourne: CSIRO Publishing, pp. 205-224.

Stark, J. M. & Redente, E. F., 1987. Production potential of stockpiled topsoil. *Soil Science,* 144(1), pp. 72-76.

Stone, E. L. & Kalisz, P. J., 1991. On the maximum extent of tree roots. *Forest Ecology and Management,* Volume 46, pp. 59-102.

Stuwe J, J. & Parson, R. F., 1977. Themeda australis grasslands on the basalt plains, Victoria: Floristics and management effects. *Australian Journal of Ecology,* Volume 2, pp. 467-76.

Thackway, R., 2010. In: D. Lindenmayer, R. Hobbs & A. Bennett, eds. *Towards a framework for describing and mapping vegetation condition: observations from temperate woodlands. Chapter 31, pp 261-270Woodland Conservation and Management.* s.l.:CSIRO Publishing.

Thackway, R., 2012. *Mulligans Flat Nature Reserve. Ver.1. VAST-2: Tracking the Transformation of Australia's Vegetated Landscapes,* Brisbane: Australian Centre for Ecological Analysis and Synthesis, University of Queensland.

Thackway, R., 2014. *VAST-2 Tracking the Transformation of Vegetated Landscapes, Handbook for recording site-based effects of land use and land management practices on the condition of native plant communities, Version 3.0,* Brisbane: The University of Queensland .

Thackway, R., in press. Tracking anthropogenic influences on the condition of plant communities at sites and landscape scales. In: A. Z. Almusaed, ed. *Landscape Ecology.* Rijeka, Croatia: InTech ISBN: 978-953-51-4809-8.

Thackway, R. & Lesslie, R., 2006. Reporting vegetation condition using the Vegetation Assets, States and Transitions (VAST) framework. *Ecological Management and Restoration,* 7(S1), pp. S53-S62.

Thackway, R. & Lesslie, R., 2008. Describing and mapping human-induced vegetation change in the Australian landscape. *Environmental Management,* Volume 42, pp. 572-590.

Thackway, R., Lymburner, L. & Guerschman, J. P., 2013. Dynamic land cover information: bridging the gap between remote sensing and natural resource management. *Ecology and Society,* 18(1): 2(http://dx.doi.org/10.5751/ES-05229-180102).

Thackway, R. & Specht, A., 2015. Synthesising the effects of land use on natural and managed landscapes.. *Science of the Total Environment,* Volume 526, p. 136–152.

Thrall, P.H., Laine, A., Broadhurst, L.M., Bagnall, D.J. and Brockwell, J. 2011. Symbiotic effectiveness of rhizobial mutualists varies in interactions with native Australian legume genera. *PLOS One* 6(8): e23545. doi:10.1371/journal.pone.0023545.

Tibbett, M., 2015. *Mining in ecologically sensitive landscapes.* Clayton South: CSIRO Publishing.

Tongway, D. J. & Ludwig, J. A., 2011. *Restoring disturbed landscapes, putting principles into practice.* Washington: Society for Ecological Restoration International, Island Press.

Trade and Investment Regional Infrastructure and Services (DTIRIS), 2011. *(2012), Guidelines to the Mining, Rehabilitation & Environmental Management Process. NSW Government, Sydney NSW..*
[Online]
Available at:
http://www.resourcesandenergy.nsw.gov.au/__data/assets/pdf_file/0009/475434/ESG3-Mining-Operations-Plan-MOP-Guidelines-September-2013.pdf
[Accessed 5 April 2016].

Trudgill, S. T., 1988. *Soil and vegetation systems - contemporary problems in geography.* 2nd ed. Oxford : Clarendon Press.

Visser, S., Fujikjawa, J., Griffiths, C. L. & Parkinson, D., 1984. Effect of topsoil storage on microbial activity, primary production and decomposition potential. *Plant and Soil,* Volume 82, pp. 41-50.

Walker, L. R., Walker, J. & Hobbs, R. J. eds., 2007. *Linking successand ecological restoration.* New York: Springer.

Warcup, J.H. 1980. Ectomycorrhizal associations of Australian indigenous plants. *New Phytology* 85, 531-535.

West, P. W., Cawsey, E. M., Stol, J. & Freudenberger, D., 2008. Firewood harvest from forests of the Murray-Darling Basin, Australia. Part 1: Long-term, sustainable supply available from native forests. *Biomass and Bioenergy,* Issue 12, p. 1206–1219.

Whitaker, O., 2016. *Manager NaturalCaptital* [Interview] (31 March 2016).

Whitehaven Coal, 2015. *Tarrawonga coal mine - white-box yellow-box blakely's red-gum woodland endangered ecological community implementation plan. January 2015. Project No. WHC-24 Document No. 00646570.docx,* s.l.: Whitehaven Coal .

Wildman, H., 2009. *Managing microorganisms to improve mine site rehabilitation success,* Lapstone: Microbial Management Systems.

Williamson, J. C. & Johnson, D. B., 1990. Determination of the activity of soil microbial populations stored and restored soils aat opencast coal sites. *Soi Biol. Biochem,* 22(5), pp. 671-671.

Willis, T., 2014. *Glencore Mangoola Coal Developing Natural Landform in Mine Overburden Rehabilitation.* [Online]
[Accessed 25 April 2016].

Wilson, N. & Gibbons, P., 2014. Microsite factors influencing Eucalyptus regeneration intemperate woodlands. *Ecological Management & Restoration,* Volume 15, pp. 155-157.

Windsor, D. & Clements, A., 2001. A Germination and Establishment Field Trial of Themeda australis (Kangaroo Grass) for Mine Site Restoration in the Central Tablelands of New South Wales. *Restoration Ecology,* Volume 9, pp. 104-110.

Windsor, D. M., Clements, A., Nolan, M. B. & Sandercock, I. H., 2000. Recreating a eucalypt woodland on a gold mine in the Central Tablelands of New South Wales. In: *Temperate woodlands in Australia. Biology, conservation, management and restoration.* Sydney: Surrey Beatty and Sons, p. 298–317.

Woodall, G. S., 2010 . *Improving the Direct Sowing of Commercial Native Plants in Agricultural Lands of Southern Australia,* Barton: Rural Industries Research and Development Corporation.

Wright, A., 2016. *Field visits to working coal mines and rehabilitation sites associated with Whitehaven Coal, Gunnedah* [Interview] (15 April 2016).

Yapp, G., Walker, J. & Thackway, R., 2010. Linking vegetation type and condition to ecosystem goods and services. *Ecological Complexity,* 7:3(doi.org/10.1016/j.ecocom.2010.04.008), pp. 292-301.

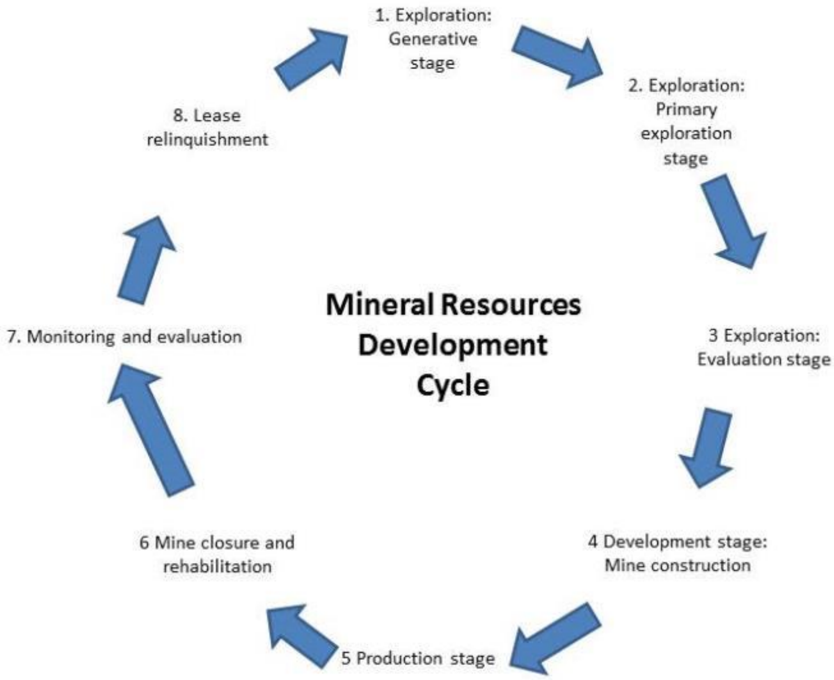
Yates, C. & Hobbs, R., 1997. Temperate Eucalypt Woodlands: a review of their status, processes threatening their persistence and techniques for restoration. *Australian Journal of Botany,* Volume 45, pp. 949-973.

Glossary

Ameliorant	Substances that are added to ameliorate a topsoil and or a reshaped final landform derived from various mined substrates (e.g. gypsum, fertilizer, mulch, hay, biosolids).
Amelioration	A process used to ameliorate limiting factors to plant growth or soil stability occurring in an area given substrate.
Attribute	Measurable aspects of an ecological attribute that inform stakeholders of its status or trend.
Base-line studies	Pre-mining surveys that are used to assess the condition and extent of plant communities and establish the modification of key indicators including; soil microbial resources, reproductive potential of plants, seed bank resources, soil carbon and nutrient resources and species composition relative to a reference state.
Criteria	An aggregate grouping of one or more indicators of the condition of a plant community summarising the effects of land management practices
Indicator	A summary descriptor used to characterize the condition of a plant community to the effects of land management practices. Indicators are populated from attributes recorded for and about a particular area using various complementary and equivalent methods. Information used to populate indicators come from various sources including; quantitative or qualitative or a combination of both.
Reference Sites	Provide an analogue for rehabilitation goal setting and as comparative areas used to assess of how rehabilitation areas are progressing.
Reference state	Reference states are a representative area of a plant community that is in a condition state: e.g. unmodified (VAST class I) or minimally *Modified* (Table 1).
Rehabilitation Areas	Mined areas that have been reshaped and soil overlain and revegetated with vegetation and other land cover types.
Resilience	The capability of an ecosystem to recover after a stress event like fire or drought. Recovery implies returning close to a pre-disturbance state without permanent loss of components or functions.
Soil-landscape unit	A site is an area of uniform soil and topographic features and pre-European vegetation communities considered to be representative of a dominant landscape element. A landscape element could be plains, depressions, flats and lower slopes, mid slopes, upper, plateau and ridge lines
Subsoil	The soil layer 10 to 20 cm below the surface, which is exposed when the top 10 to 15 cm of topsoil is scraped away.
Substrate	Unconsolidated material that will be rehabilitated or restored including spoil, chitter and subsoil.
Topsoil	Soil surface down to 10 or 15 cm that is stripped for use in rehabilitation. Topsoil is used to provide a seedbed and where derived from unmodified states, capture any seed bank and microbes present.

Appendix 1 - Mineral Resources Development Cycle and ecosystem condition states

The mining industry operating in Australia's landscapes has developed business rules for working with local, state and national regulators of native vegetation type, extent and condition. The Mineral Resources Development Cycle (MRDC) is one such business rule. Mining companies with operational mining projects are aware that their practices modify and create land cover types as they proceed through the cycle, however they may not be fully aware of theory and practice of better managing for native vegetation condition outcomes in particular phases in the MRDC.



Modified from Minerals Council of Australia http://www.minerals.org.au/resources/gold/life_cycle_of_a_mine#

Eight phases involved in a Mineral Resources Development Cycle.

Mining is just another transforming land use. A framework for classifying and describing the degree of transformation in terms of extent and condition is the VAST framework (Table 1) (Thackway & Lesslie, 2006) (Thackway & Lesslie, 2008). For example, a mine in the Production stage (MRDC phase 5) creates landscapes that can be classified as *Removed* i.e. VAST class VI (Table 1). In such a condition state, clearly there is no native vegetation.

Transitions from one native vegetation condition class (e.g. *Unmodified*) to another (e.g. *Transformed* (Table 1) occur because the land manager/s (e.g. a grazier) applies land management practices over time to bring about major changes in a plant community's vegetation structure, species composition and function. These three elements of native vegetation in the VAST framework are referred to as diagnostic criteria (Table 1) or as components in the VAST-2 framework (Table 2).

Equally, transitions from a non-native condition class (e.g. MRDC phase 5 - a production stage mining operation which is classified as *Removed* VAST class VI) to a native vegetation condition class (e.g. MRDC phase 7 - Monitoring and evaluation which is classified as Adventive VAST class VI or *Transformed* (Table 1) do occur because the mining sector has learnt to apply land management practices over time to actively restore, reconstruct or reinstate a plant community's vegetation structure, species composition and function. Fundamentally achieving successful transitions between condition states requires a high level of knowledge, skill and experience of how land management practices/interventions affect key criteria and indicators of a plant community's vegetation structure, species composition and function.

The eight phases in the MRDC have an associated and predictable set of vegetation modification (condition state) outcomes. In the context of a mineral lease these condition states might include: areas which are fully natural or unmodified representing a reference state; bare areas where the vegetation cover is removed during mining and before closure; early, mid and/or late stage rehabilitation areas which were previously mined materials or a mine void; areas of modified native vegetation selected as offset areas; restored offset areas. Each of these condition states is the outcome of a collective suite of prior land management practices (actions) which reflects their severity, magnitude, duration and frequency affecting criteria and indicators within and across soil landscape units. Collectively the effects of land management practices result in the condition states described in Table 1.

Using the above framework, our preliminary synopsis in relation to the vegetation condition outcomes of the eight phases the MRDC is:

- During the exploration stage (phases 1, 2 & 3) it is likely that there are no interventions affecting the condition and extent of the native vegetation.
    - From Table 1 it is likely that the lease will comprise of areas which correspond to VAST classes I, II &/or III). This can be surmised because its tenure was a state forest.
    - From Table 2 and a corresponding land management chronology; it is likely that the function of the native vegetation has been minimally modified and that the structure and composition are moderately modified. By experience, most state forest involving the management of native vegetation are classified as *Modified*. These surmises would be expected to be mirrored in the corresponding criteria and indictors. The soils are expected to have quite a viable seed bank.
    - During phase 7 it can be surmised because it is a state forest that the primary management regime is Harvesting biomass, fruit, fibre; the secondary regime is Encouraging regeneration, enhance growth, maturity & reproduction; tertiary regime is Monitor health & vitality
- During the Development stage: Mine construction and the Production stage (phases 4 and 5);
    - From Table 1 it is likely that the native vegetation is removed (i.e. VAST class VI).

- From Table 2 and a corresponding land management chronology it is likely that the soils being dug stripped from sources such as a State Forest are expected to have quite a viable seed bank.
- During phase 7; it is likely that the primary management regime is Degrade, extirpate or remove and/or replace the native vegetation; the secondary regime is to conservatively manage the topsoil for reuse in near future to Re-establish, restore and/or rehabilitate the plant community; and the tertiary regime is to develop appropriate suppliers for the sourcing of sufficient quantities of high quality local provenance seed and seedlings for rehabilitation.

- During the Mine closure and rehabilitation stage (phase 6);
  - From Table 1 it is likely that the vegetative cover is transition from *Removed* (i.e. VAST class VI) to Replaced – *Managed* (i.e. VAST class V). The topsoil from stages 4 & 5 will be laid over the unconsolidated rock mounds. A cover crop of non-native or native species or a combination of both is likely to be planted. (i.e. VAST class V or VAST IV).
  - From Table 2 and a corresponding land management chronology it is likely that there will be issues with the key functional criteria and indicators. It will be necessary to reconstruct, restore and reinstate these criteria: soil nutrients, soil hydrology, soil biology, soil structure and the reproductive potential of the overstorey and understorey. During this phase it will be necessary not to reinstate a fire regime too early. Critical to achieving this level of resilience will be an adaptive approach to the use land management practices to ensure the criteria and indicators are gradually reinstated. The timing for reinstating functional criteria before structure and composition is critical.

    Key threats to successful reinstating of functional criteria include: substrate failures, toxicity of the substrate; poor nutrient management; poor development of soil structure; poor development of soil biology; poor development of soil hydrology.

    Key threats to successful reinstating of structural and composition criteria include: inappropriate clearing of the early stages of regeneration of native vegetation, inappropriate herbicide use; incursions from livestock, incursions from exotic and native plants; incursions from exotic and grazing native animals; incursions of wildfire; poor germination, establishment, development and maturity of sown plants; drought during key growing seasons.
  - During phase 7; it is likely that the primary management regime is likely to be Re-establish, restore and/or rehabilitate the key criteria and indicators; the secondary management regime is likely to be Encourage regeneration, enhance growth, maturity & reproduction; the tertiary management regime is likely to be Monitor health & vitality.
- During the Monitoring and evaluation stage (phase 7)
  - From Table 1 it is likely in the early stages (2-5 years) of rehabilitation; native vegetation condition will comprise vegetative states including: Replaced and managed (VAST class V) or Largely replaced and plant community is adventive (VAST class IV). It is likely that it will take many years (10-30 years) after rehabilitation to achieve a Transformed native vegetation (the *Transformed* (Table 1)). It is likely that

it will take many years (40-60 years) after rehabilitation to achieve a Transformed native vegetation (VAST class II).

- From Table 2 and a corresponding land management chronology progress toward reinstating a native vegetation cover state (e.g. *Transformed* (Table 1)) can be assessed using the degree to which key criteria and indicators have been reinstated or restored. The intent of phase 7 is to for the native vegetation to have germinated, established and be on a development pathway to a level of resilience that it can withstand a major perturbation/s e.g. insect attack, wildfire, drought, flood or damaging storm /cyclone.
- During phase 7; it is likely that the primary management regime is Monitor health & vitality; the secondary management regime is likely to be Encourage regeneration, enhance growth, maturity & reproduction; the tertiary management regime is likely to be No intervention to the native vegetation.

- At the point of Lease relinquishment stage (phase 8)
  - From Table 1 it is likely that the vegetative condition will be either a Transformed state (*Transformed* or *Modified* (Table 1)). It is important to note in order to have achieved a Modified state i.e. VAST class II, this requires considerable time and close attention to the management of key indicators to ensure that all three components of structure, composition and function are demonstrably established and developing.
  - From Table 2 and a corresponding land management chronology progress toward reinstating a condition vegetation state (e.g. *Transformed* class (Table 1) or *Modified*) can be assessed using the degree to which key criteria and indicators have been reinstated or restored. The intent of phase 8 is to for the native vegetation to have developed to a level of resilience that it can withstand a major perturbation/s e.g. insect attack, wildfire, drought, flood or damaging storm /cyclone.
  - During phase 7; it is likely that the primary management regime is Monitor health & vitality; the secondary management regime is likely to be Encourage regeneration, enhance growth, maturity & reproduction; the tertiary management regime is likely to be No intervention to the native vegetation.

Appendix 2 - Recommended leading management practices for high integrity Grassy Box Woodland sites.

Recommended leading management practices for high integrity of Grassy Box Woodland sites are presented this Appendix. It presents a list of criteria and indicators matching those in Table 2 and the accompanying leading site management practices recommended for the maintenance and improvement remnant patches of Grassy Box Woodland sites which are either unmodified or minimally modified condition states.

NB: the VAST-2 criteria and indicators match those in Table 2. High integrity includes *Unmodified* and *Modified* condition states that are defined in Table 1.

Components	**VAST-2 criteria**	**VAST-2 indicators**	**Best Practice Site Management Practices to maintain and improve reference state Grassy Box Woodland [5]**
Function	Soil hydrology	3, 4	Do not direct run-off (from roads, urban developments, contour banks) into remnant areas.
		3, 4	Do not divert existing run-on from remnant areas (e.g. diversion drains).
	Soil structure	6	Avoid physical disturbance (e.g. cultivation, ripping, excavation).
		6	Avoid soil compaction from vehicles/machinery or stock camps.
	Soil nutrient status	8	Avoid chemical changes (e.g. use of fertilisers or soil ameliorants).
	Soil biological status	10	Prevent firewood collection or the "tidying up" of fallen dead timber and leaf litter.
		10	Prevent the stockpiling of topsoil or overburden within remnant areas.
	Reproductive potential	12	Ensure remnant areas are rested at appropriate times, for example when perennial native ground cover species are flowering and seeding.
		12	Limit grazing during drought periods.
		12	Grazing levels should not be increased above historical levels. Where a site has never before been grazed by livestock, an alternative (e.g. fire, no intervention) should be used for management.
		12	Timing of burns must be considered in relation to the flowering and seeding of native and exotic species. Where possible burns should be carried out after natives have seeded but before weeds flower and seed.
	Disturbance regime	1	Any burning should be applied to remnants in mosaics (i.e. burning small areas at staggered intervals) to allow survival of soil and ground fauna (including invertebrates, amphibians and reptiles) and promote diversity in the states of the ecological community.
		1	Sites where burning is practiced should retain unburnt areas, to provide refuges for species of fauna and flora that may be intolerant of fire.

[5] Adapted from Table 4. Current best practice site management practices for the continued existence of box-gum grassy woodland (Department of Environment, Climate Change and Water, NSW, 2010)

Components	VAST-2 criteria	VAST-2 indicators	Best Practice Site Management Practices to maintain and improve reference state Grassy Box Woodland [5]
		2	The minimum fire interval suggested for Box-Gum Grassy Woodlands is five years, with a maximum interval of 40 years[6]. Fire regimes implemented should have regard to the floristic composition and condition of the remnant. For example, remnants dominated by Snow Grass and Kangaroo Grass were found to regenerate well with autumn burning cycles approximately every 5-8 years, where this had historically occurred (Prober et al. 2008). Such high frequency burning cycles may negatively impact other native species, however, and further research is required before burning regimes can be explicitly determined.
Structure	Overstorey structure	14	Prevent changes which will result in prolonged shading (e.g. dense tree plantings).
		14	Prevent the removal of regenerating trees and shrubs within remnant patches.
		14	Maintain complete structure of woodland without allowing a full canopy to develop, shading out understorey species.
		14	Plant trees and shrubs at natural grassy woodland densities.
	Understorey structure	17	Maintain a minimum of 80% ground cover at all times and biomass at an appropriate level to the region and season. Monitor outcomes to determine effectiveness and adapt management efforts.
		18	Do not plant indigenous native trees/shrubs in high quality and/or small derived grassland sites.
Composition	Overstorey composition	19, 20	Use high quality seed. Where practical this should be of local provenance, but high quality non-local seed should be used in preference to low quality local seed.
		20	Implement a weed control program to control weed invasion, wildlings from adjacent tree plantings (e.g. Radiata Pine and European Olives) and garden escapees. Implement a buffer zone to help control weed introductions and protect remnant from herbicide drift.
		20	Weed control should use spot-spraying, basal spraying, stem injection or cut and paint application methods.
	Understorey composition	21, 22	Prevent the introduction of exotic pasture species (i.e. pasture improvement).
		22	Prevent the introduction of non-indigenous native species.
		22	Ensure machinery hygiene protocols are implemented to prevent the spread of weeds.
		22	Be aware that some weed species (e.g. Coolatai Grass) increase with burning.
		21, 22	Use high quality seed. Where practical this should be of local provenance, but high quality non-local seed should be used in preference to low quality local seed.
		20, 21	Weed control should use spot-spraying, basal spraying, stem injection or cut and paint application methods.
		21, 22	Avoid overspray and minimise impacts on non-target species.
		21, 22	Prevent re-establishment of weeds in treated areas especially resultant bare patches.
	Habitat		Prevent rock removal.
	Habitat		Prevent the removal of standing dead hollow trees.
	Landscape		Ensure existing links are maintained between Box-Gum Grassy Woodland remnants and/or between Box-Gum Grassy Woodland and other native vegetation types, for example grassland, woodland, forest, riparian and/or wetlands.
	Landscape		Expand sites to increase viability where possible.

[6] Adaptive Management Guidelines for Box Gum Grassy Woodlands, produced by the NSW Department of Environment, Climate Change and Water and the Grassy-Box Woodland Conservation Management Network. Available at http://gbwcmn.net.au/files/AdaptiveManagement09.pdf .

Components	VAST-2 criteria	VAST-2 indicators	Best Practice Site Management Practices to maintain and improve reference state Grassy Box Woodland [5]
	Landscape		Protect areas of Box-Gum Grassy Woodland from adjacent land use (e.g. urban and agricultural development) that may potentially impact on its integrity.

Appendix 3 - Applications of Vegetation Assets, States and Transitions (VAST)[7]

Client	Year	Purpose	Agro-climatic region/s (Figure 1)	Report/publication
Coal & Allied Industries Limited	2013	Use VAST as the framework for providing detailed hands-on guidance, based on research and lessons-learnt from previous experience, on how to successfully restore modified plant communities in a sustainable and effective manner. Using VAST as framework for monitoring and reporting changes in vegetation condition	Sub Tropical Moist	Thackway, R., Eriksson, C., and Tierney, D., (2013). *Warkworth Mine, Warkworth Sand Woodlands Restoration Manual*. Report prepared for Coal & Allied Industries Limited. Niche Environment and Heritage, Parramatta. Pp 64.
Australian Government, Department of Environment	2011	To demonstrate changes in the condition of Australia's major vegetation groups	All 10 regions whole of Australia	State of the Environment report 2011, Chapter 2.3 Vegetation (SoE 2011)
Office of Environment and Heritage, Sydney	2011	Assessment of condition of native vegetation at a regional scale	Temperate cool season	Davidson, I., Sheahan, M., and Thackway, R. (2011). An innovative approach to local landscape restoration planning: Lessons from practice. *Ecological Management & Restoration* 12: 175–188. http://onlinelibrary.wiley.com/doi/10.1111/j.1442-8903.2011.00607.x/abstract
Australian Government Department of Agriculture, ABARES	2010	Developing a national dataset on the condition of Australia's major vegetation groups	All 10 regions whole of Australia	Lesslie, R., Thackway, R., and Smith, J. (2010). *A national-level Vegetation Assets, States and Transitions (VAST) dataset for Australia (version 2)*. Bureau of Rural Sciences, Canberra. http://data.daff.gov.au/data/warehouse/pe_brs90000004193/VASTv2Data_20100320_ap14.pdf

[7] Thackway, R. and Lesslie, R. (2008). Describing and mapping human-induced vegetation change in the Australian landscape. *Environmental Management*, 42: 572-590. http://dx.doi.org/10.1007/s00267-008-9131-5

Client	Year	Purpose	Agro-climatic region/s (Figure 1)	Report/publication
Department of Defense, Environment Directorate	2016	Using VAST and VAST-2 as a system for assessing condition of Hanson's Farm Conservation area and assessing the potential for the area to provide an offset for developments at the Amberley RAAF Base	Tropical warm season moist	Thackway, R and Pearson, S. (2016). Amberley RAAF Base, Assessing changes in the extent and condition of native vegetation on Hanson's Farm Conservation Area over time. Report prepared for the Department of Defence, Environment Directorate, Canberra.
The Mulloon Institute	2015-current	Using VAST-2 as a system for tracking the recovery of grassy open woodland following adoption of holistic landscape management practices	Temperate cool season	Thackway (in prep). *Tracking change and trend in vegetation condition at selected sites in the Mulloon Creek Catchment, Bungendore, NSW.*
Wentworth Group of Concerned Scientists	2015	Using VAST-2 as a framework for developing a *Protocol for Constructing a Native Vegetation Condition Account*	10 NRM regions Australia	Thackway R., Cosier P., McIntosh E., Saunders D., Possingham H. and Sbrocchi C.D. (2015). *Draft Protocol for Constructing a Native Vegetation Condition Account. Australian Regional Environmental Accounts Working Paper Series (1/5)*. Wentworth Group of Concerned Scientists, Sydney. http://wentworthgroup.org/wp-content/uploads/2015/11/Accounting-for-Nature-Technical-Report-Working-Paper-1.pdf
Australian Journal Mining's Mineral Sands	2014	Invited paper 14th Annual Australian Journal Mining's Mineral Sands Conference	Sub Tropical Moist	**Thackway, R. (2014). Tracking sand dune transformation before, during and after sand dune mining, Myall Lakes, NSW, a case study.** The 14th Annual Australian Journal Mining's Mineral Sands Conference, at the Rydges, Melbourne, Vic on 4th & 5th March 2014 http://static1.squarespace.com/static/56e0eb398259b580b4ade479/t/570f047e40261da404b66e5a/1460601998335/VAST_Library_poster.pdf
Australian Government Department of Agriculture, ABARES	2013	Using VAST-2 to monitor and report changes in the conservation and sustainable management of native forests	Sub Tropical Moist	State of the Forests Report (2013) pages 380-382 http://data.daff.gov.au/data/warehouse/9aaf/sofr/2013/SOFR2013crit7_FrameForestConserv_v1.0.0.pdf
Charlie Massy, Severn Park, Cooma, NSW	2013	Tracking the transformation of Chandler paddock a grassy open woodland used for grazing sheep	Temperate cool season	Yapp, GA. and Thackway, R. (2015). Responding to Change — Criteria and Indicators for Managing the Transformation of Vegetated Landscapes to Maintain or Restore Ecosystem Diversity, Biodiversity in Ecosystems - Linking Structure and Function, Dr Juan A. Blanco (Ed.), ISBN: 978-953-51-2028-5, InTech, Available from: http://www.intechopen.com/books/biodiversity-in-ecosystems-linking-structure-and-function/responding-to-change-criteria-and-indicators-for-managing-the-transformation-of-vegetated-landscapes

Client	Year	Purpose	Agro-climatic region/s (Figure 1)	Report/publication
Soils for Life an Outcomes Australia Program	2013	Monitoring, evaluating, reporting improvement and tracking of the impacts of land management outcomes on native vegetation structure, composition and function in grazing of native grasslands	Temperate cool season	Description of the VAST 2 workshop, at Jillamatong, Braidwood, 13 November 2013. VAST-2 resources http://www.soilsforlife.org.au/vast2
Western Australian Department of Environment and Conservation, Kalgoorlie and the CSIRO Division of Ecosystem Sciences	2013	Assessing the condition of salmon gum woodlands as part of the TERN Supersite, Credo Station, Kalgoorlie and providing options for future restoration	Dry	Thackway, R., (2013). *Tracking change and trend in vegetation condition at selected sites on Credo Station, Great Western Woodlands.* Report prepared for the Western Australian Department of Environment and Conservation, Kalgoorlie and the CSIRO Division of Ecosystem Sciences, Perth. May 2013. Westerlund Eco Services, Rockingham, Western Australia, revised 23 September 2013. p36. http://issuu.com/vasttransformations/docs/credostation
Institute of Foresters of Australia	2013	Invited paper, 2013 National Conference, Institute of Foresters of Australia, Canberra	Mediterranean, Sub Tropical Moist, Temperate cool season	Thackway, R., (2013). Applying a system for tracking the changes in vegetation condition to Australia's forests. In: Brown, A.G., Wells, K.F., Parsons, M. and Kerruish, C.M. (eds) (2013) Managing our Forests into the 21st Century. Proceedings of national conference, Institute of Foresters of Australia, Canberra, ACT, Australia, 4–7 April 2013, pp. 79-91.