Evaluating methods for assessing native ecosystem mine rehabilitation success

Technical paper

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Disclaimer

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Executive Summary

This technical report is the third of three papers prepared to support operators involved in mine rehabilitation to achieve native ecosystem outcomes. The first technical paper examines the differences between *historical*, *hybrid* and *novel* ecosystems in the context of native ecosystem mine rehabilitation, particularly given the biophysical limitations of land post-mining. The technical paper and a second paper, a stakeholder survey report on *Evaluating native ecosystem rehabilitation options in Queensland*, can be found on the QMRC website.

This paper assesses common ecosystem monitoring methods for their usefulness in the evaluation of different native ecosystems rehabilitation outcomes in Queensland. Methods include the Queensland Biodiversity and Ecology Information System (QBEIS) site data collection method, BioCondition assessment, ecosystem services valuations, Landscape Function Analysis (LFA), Ecosystem Function Analysis (EFA), and others.

Successful native ecosystem rehabilitation must result in a self-sustaining functional system. For *natural* ecosystem rehabilitation, methods must be able to measure the similarity of the site to the vegetation community in the target RE. For *novel* ecosystems, it is not feasible to compare the sites to vegetation communities within specific REs. However, monitoring methods for this type of ecosystem must determine if the rehabilitation is dominated by native species and assess the delivery of beneficial environmental outcomes. Measuring the success of *hybrid* ecosystem rehabilitation will depend on whether this ecosystem will be managed to become more like a *natural* ecosystem or will retain novel aspects but deliver beneficial environmental outcomes.

The Queensland Biodiversity and Ecology Information System site data collection method (QBEIS method) is the standard survey technique for native ecosystems in Queensland. We recommend QBEIS method as the core native ecosystem rehabilitation monitoring technique in Queensland. The key components the method captures that are pertinent to native ecosystem mine rehabilitation are:

- landform classification
- a list of all species present
- basal area/woody stems diameter
- percentage cover
- stem density measures of abundance.

BioCondition is a quantitative condition assessment framework for Queensland that measures how well a terrestrial ecosystem is functioning for biodiversity values. Almost all of the components in BioCondition are also in the QBEIS site data collection method. The coarse woody debris (CWD) attribute, important to mine rehabilitation, is captured in BioCondition but not in the QBEIS method.

In order to demonstrate beneficial environmental outcomes, specific ecosystem services may need to be documented within mine rehabilitation. Quantifying ecosystem services is complex; and robust indicators do not exist for all services. Nonetheless, we discuss potential avenues for monitoring some of these services using environmental condition indices within the Accounting for Nature framework.

Landscape Function Analysis (LFA) is a soil condition monitoring procedure. It measures soil and surface condition to assess the function of an ecosystem in terms of resource use and recycling. LFA is an effective tool for assessing the overall biophysical characteristics of a site. It has been observed that LFA indices tend to plateau once soil structure has stabilised, and vegetation cover has maximised. Resultantly, we do not recommend the use of LFA to measure mine rehabilitation success when compared to native ecosystems, *per se*, but the method may still be informative for early monitoring of rehabilitation.

As the base survey method for all classes of ecosystem rehabilitation, we recommend using the QBEIS site data collection method.

1 Introduction

In Queensland, the objective of mine rehabilitation is for land disturbed by mining to attain a ‘stable condition’, which is defined as land that is safe, stable, does not cause environmental harm, and is able to sustain a post-mining land use (PMLU) (*Environmental Protection Act 1994* (Qld), s111A). Mining companies need to articulate achievable and measurable rehabilitation milestones and milestone criteria to demonstrate progress towards these rehabilitation objectives via Progressive Rehabilitation and Closure (PRC) plans. A commonly proposed PMLU is native ecosystem, though there is not a state-wide definition of ‘native ecosystem’ for the purposes of rehabilitation, and existing rehabilitation milestone criteria for this very broad PMLU vary considerably between sites.

Our previous work (Spain et al., 2023) explored in detail the range of native ecosystems that are achievable from rehabilitation efforts in highly disturbed landscapes, the biophysical limitations that contribute to differing ecosystem outcomes, and leading practice management approaches to maximise environmental outcomes from native ecosystem rehabilitation. Recognising that there is a variety of native ecosystem outcomes from rehabilitation of highly disturbed sites, the aim of the present work is to outline leading practice methods for assessing native ecosystem rehabilitation success across Queensland.

Evaluating rehabilitation success is fundamental to PRC planning, rehabilitation monitoring and final mine closure (Glenn et al., 2014; Hooper et al., 2016). A suite of indicators may be used to evaluate ecosystems, including structural parameters, diversity indices and functional attributes e.g., Gastauer et al. (2018). However, which indicators to use, when, and how to monitor them consistently for rehabilitation (Humphries, 2015; Kollmann et al., 2016), is complex and unclear, further compounded by the range of native ecosystem outcomes resulting from the biophysical limitations that post-mining landscapes present.

This paper assesses common ecosystem monitoring methods for their usefulness in the evaluation of different native ecosystems rehabilitation outcomes in Queensland. Methods include benchmarking against reference ecosystems using Queensland Biodiversity and Ecology Information System (QBEIS) site data collection method, BioCondition assessment, ecosystem services valuations, Landscape Function Analysis (LFA), Ecosystem Function Analysis (EFA), and others.

2 Rehabilitation options

Depending on the severity of the mining disturbance and the biophysical limitations of the site that remain after leading practice rehabilitation techniques, rehabilitation plans may target different classes of native ecosystems: *natural*, *hybrid* or *novel* (Table 1; Doley et al. 2012, Doley and Audet 2013). *Natural* ecosystems resemble vegetation communities within regional ecosystems (REs)[1] (Neldner et al., 2022), that either historically occurred on the mine site or exist within the bioregion (*substitute* ecosystems; Table 1).

Where a *natural* ecosystem was unable to be developed, *novel* ecosystems may develop. *Novel* ecosystems are stable ecosystems comprising new assemblages of abiotic and biotic attributes that do not resemble a *natural* ecosystem. *Novel* ecosystems are generally the unintended result of human alteration of the environment (Hobbs et al., 2014), and by definition they have crossed an irreversible disturbance threshold and cannot be restored to a natural state by management intervention (Doley et al., 2012; Doley and Audet, 2013; Erskine and Fletcher, 2013). In some cases, planned *novel* ecosystems (i.e., *designer* ecosystems, Table 1) might be a mine rehabilitation objective. Where these are established to meet native ecosystem rehabilitation goals, such as biodiversity improvement (Higgs, 2017), they might be considered as a native ecosystem PMLU. However, since the species assemblages that comprise them are not representative of *natural* ecosystems and they cannot be manipulated towards a *natural* ecosystem by management intervention, they are considered here with *novel* ecosystems.

[1] REs are a vegetation community or communities in a bioregion that is consistently associated with a particular combination of geology, landform and soil (Neldner et al. 2022).

Hybrid ecosystems contain elements of *natural* ecosystems as well as novel biotic and abiotic attributes. The species assemblages that characterise *hybrid* ecosystems do not naturally occur in REs however *hybrid* ecosystems may be manipulated to become a *natural* ecosystem via management intervention (Hallett et al., 2013; Hobbs et al., 2013). *Hybrid* and *novel* ecosystems are collectively termed *no-analogue* systems*.* A more comprehensive discussion of ecosystem rehabilitation options can be found in Spain et al. (2023).

Table 1. Rehabilitated native ecosystem classes, characteristics and management considerations

Native ecosystem class	Subclass	Characteristics of the rehabilitated native ecosystem	Management considerations
Natural	Historic	Abiotic and biotic characteristics of the RE that was present pre-mining.	Post-mining management expected to be similar to management of pre-mining RE.
Natural	Substitute	Abiotic and biotic characteristics that differ from those in the pre-mining RE, but analogous to another RE within the bioregion.	Post-mining management expected to be similar to management of REs in the surrounding bioregion.
Hybrid	n/a	Attributes and ecosystem functions are similar to those in an RE, but ecosystem is characterised by unique aspects that are not found in the desired RE.	Management action can be taken to manipulate these systems towards an RE.
Novel	Unplanned	The unintentional result of attempts to establish an RE where biophysical limitations or rehabilitation techniques have resulted in a unique and stable assemblage that does not have a *natural* analogue.	Stable ecological form that cannot be manipulated to become an RE via management intervention.
Novel	Planned	A planned native ecosystem that meets specific beneficial environmental outcomes but has no *natural* analogue (i.e., is intentionally novel). Also known as a *designer* ecosystem.	Self-sustainability unknown, though expected to require management. Cannot be manipulated to become a RE.

3 Indicators of success

Successful native ecosystem rehabilitation must result in a self-sustaining functional system. Self-sustaining functional systems are those where resources (water, plant litter, topsoil, nutrients) are mostly recycled and not lost through erosion or leaching (Tongway and Hindley, 2004), and where the system is able to maintain itself or be replaced by other successive types over time (Humphries, 2013) (Table 2). Successful establishment of vegetation and colonisation of other organisms will ensure the stabilisation of soil, which, in turn, ensures the retention of resources for the next generation. For flora of native ecosystems, a key measure of 'sustainability' is the successful recruitment of the next generation (i.e., production of flowers, seeds and surviving seedlings that will become the next adult generation).

For *natural* ecosystem rehabilitation, methods must be able to measure the similarity of the site to the vegetation community in the target RE (Table 2). This involves consideration of the components that define REs. We also discuss any considerations for dissimilarities that may arise due to the young age of the rehabilitation compared to the target REs (e.g., absence of 'large' trees, Section 5.2).

For *novel* ecosystems, it is not feasible to compare the sites to vegetation communities within specific REs. Nevertheless, these native ecosystems must be dominated by native species in order to be considered a native ecosystem PMLU (Spain et al., 2023). Therefore, at a minimum, methods must assess whether the dominant vegetation species are native. A native ecosystem PMLU that is *novel* (even if it has a mixed-PMLU goal; e.g., native ecosystem with recreation or agriculture) must deliver, or aim to deliver, beneficial environmental outcomes (Environmental Protection Regulation 2019, Schedule 8A). This necessitates the need for additional methods to assess the delivery of beneficial environmental outcomes (Section 6). Measuring the success of *hybrid* ecosystem rehabilitation will depend on whether this ecosystem will be managed to become more similar to a *natural* ecosystem or will retain novel aspects but deliver beneficial environmental outcomes (Table 2).

Table 2. Indicators of success for native ecosystem mine rehabilitation for each class of native ecosystem. Brackets indicate this aspect is included only if *hybrid* ecosystems are to be managed to become natural ecosystems.

Native ecosystem class	**Ecosystem Function (self-sustainability)**	**Native floristics[2]**	**Similarity to RE**	**Environmental benefits**
Natural	✓		✓	
Hybrid	✓	✓	(✓)	(✓)
Novel	✓	✓		✓

Sections 4 to 7 describe the monitoring methods and discusses their usefulness in the evaluation of different native ecosystems rehabilitation outcomes in Queensland (Spain et al., 2023). A summary of the key metrics used in each monitoring method for evaluating native ecosystem rehabilitation success is provided in Appendix 3.

4 QBEIS site data collection method

4.1 Natural ecosystem class

As the major defining feature of a native ecosystem is its dominant floristic structure and composition (Neldner et al., 2019), a method of measuring the structure and floristics is fundamental to assessing the success of this PMLU. The Queensland Biodiversity and Ecology Information System site data collection method (thereafter QBEIS method) is the standard survey technique used by the Queensland Herbarium to capture data on these and related metrics (Neldner et al., 2022; Queensland Herbarium, 2022). We recommend the QBEIS method as the core native ecosystem rehabilitation monitoring technique in Queensland. The key metrics which make the method suitable are discussed within Appendix 1.

Post-mining rehabilitation to achieve natural ecosystems, here Including *hybrid* ecosystems that are to be managed to become more similar to a *natural* ecosystem, would ideally progress towards the target RE(s). In Queensland, an RE is defined as a vegetation community or communities in a bioregion that is consistently associated with a particular combination of geology, landform and soil (Neldner et al., 2019). To measure the success of this progression, we recommend the same level of detail as specified for secondary site classification of REs (Neldner et al., 2022) (Table A1-1). This includes the following components:

[2] Dominant vegetation must be native species for the rehabilitation to be classed as a native ecosystem PMLU. For *hybrid* and *novel* ecosystems, less detailed floristic assessment is needed (i.e., only assessing dominant flora) than assessment of the similarity to an RE (which requires full community analysis, Section 4), unless the *hybrid* ecosystem is going to be managed towards an RE

- landform classification
- a list of all species present
- basal area/woody stems diameter
- percentage cover
- stem density measures of abundance.

4.2 *Hybrid* and *Novel* ecosystem classes

For *novel* and *hybrid* ecosystems to be classified as a native ecosystem PMLU, they must be dominated by native species (Spain et al., 2023). *Hybrid* ecosystems here include those that are to be managed to retain novel aspects and deliver beneficial environmental outcomes. This classification involves assessment of which species(s) are dominant (have highest biomass) within each vegetation strata (canopy, shrub and ground cover), and identifying them to distinguish native from non-native species. Specifically, the QBEIS method having tertiary site level of detail (Neldner et al., 2022) (Table A1-1) may be applied to *hybrid* and *novel* ecosystems. This only includes dominant or conspicuous species of the ground layer cover and all woody species, measuring or estimating their height (or height range), cover and abundance in each layer. We recommend, however, the use of secondary sites in *hybrid* and *novel* ecosystems where practical; in particular the full floristic component of this site type may be important in documenting exotic or threatened species having significance to rehabilitation management.

4.3 Measuring rehabilitation success with QBEIS

As the QBEIS is a databasing method, it does not include methods of comparison between sites. However, this is one of the main ways rehabilitation of mines can be assessed for success as it involves comparison to the target native ecosystem (RE). Direct comparison of ecosystem metrics is possible between *natural* ecosystem rehabilitation and target REs, provided these latter are specified in the Progressive Rehabilitation and Closure plans (PRC plans), or easily identified from the surrounding vegetation. However, for *novel* and *hybrid* ecosystems, by definition there are no analogous ecosystems. Nevertheless, reference sites can be informative as they constitute general targets for structural and compositional attributes. In Appendix 2, we outline the key principles applicable to the selection of reference sites for *natural* ecosystems, and the nuances of reference site selection for *novel* and *hybrid* ecosystems.

5 BioCondition

5.1 Description

BioCondition is a quantitative condition assessment framework for Queensland that measures how well a terrestrial ecosystem is functioning for biodiversity values. The degree to which the attributes of the vegetation differ from the attributes of a reference state is the mechanism by which BioCondition results are scored (Eyre et al., 2015). BioCondition was developed for remnant and regrowth vegetation on natural landforms, rather than mine rehabilitation. However, it has been successfully applied to mine rehabilitation (Neldner and Ngugi, 2014; Ngugi and Neldner, 2015; Ngugi et al., 2015). While BioCondition assesses species richness, it does not incorporate measures of species identity. Therefore, it is not suitable as a standalone measure for *natural* ecosystem rehabilitation.

5.2 Advantages to the BioCondition method

Whilst almost all of the components in BioCondition are also in the QBEIS site data collection method, the BioCondition manual (Eyre et al., 2015) often describes them in more of a procedural manner (including graphical figures) than in Neldner et al. (2022). However, Neldner et al. (2022) contains more detail on attribute designations, and certain technical considerations such as the rules for defining vegetation strata.

Neldner & Ngugi (2014) omitted these parameters, as well as the measure of large trees in their application of BioCondition to rehabilitation at Meandu mine. Specifically, they omitted:

(i) landscape attribute scores (size, context and connectivity of the ecosystem, weighted at 10%, 5% and 5% respectively; (Eyre et al., 2015);

(ii) large trees and coarse woody debris (CWD) attributes, 15% and 5% respectively.

However, inclusion of a modified CWD assessment will encourage leading practice rehabilitation approaches, for instance by incorporating habitat structures such as emplacement of salvaged dead trees, CWD, and/or nest boxes (Nichols and Grant, 2007; Cristescu et al., 2012). Capturing data on these parameters is important since CWD and other habitat features are pivotal for facilitating colonisation by invertebrate detritivores, soil organisms, some mammals and trophic cascades that depend on them (Cristescu et al., 2012). We note that CWD is measured in the BioCondition method and not in the QBEIS method.

The provision to omit large tree measurements makes sense since mine rehabilitation will not have large trees, which generally take >50 years to develop. Nevertheless, basal area is an included measure in BioCondition and QBEIS methods, which will capture the trajectory of tree growth.

There may be value in retaining the landscape attribute scores where operations across the lease are attempting to increase landscape connectivity (see Section 5 of Spain et al., 2023). Such an effort will only be applicable for mines that have remnant vegetation neighbouring their leases or are trying to connect rehabilitation efforts to neighbouring biodiversity offset areas (e.g., Werris Creek mine, NSW).

5.3 Calculation of BioCondition scores from reference sites

The requirement of the BioCondition method for comparison to reference REs may result in some *novel* or *hybrid* ecosystems having lower condition scores that do not reflect whether the ecosystem is functional and/or performing environmental benefits. Therefore, the use of the full suite of BioCondition metrics, when comparing to reference REs, is not recommended for *novel* ecosystems (or *hybrid* ecosystems that differ substantially from target REs). Reference sites will still be informative for general structural and compositional targets (Appendix 2). Instead, these metrics can serve as a guide for value ranges. Additionally, area-weighted average scores for each BioCondition metric may be calculated and compared within permanent plots across time (see Section 6.3) in order to measure the trajectory of rehabilitation sites.

6 Beneficial environmental outcomes

All PMLUs need to be viable with regard to the land in the surrounding region. Where the PMLU is not consistent with the pre-mining land use, a development approval or, for example, with a planning instrument under State or Commonwealth legislation, then the PMLU needs to deliver a “beneficial environmental outcome” (*Environmental Protection Regulation 2019* (Qld), Schedule 8A part 3). “Beneficial environmental outcomes” are not currently defined in legislation. Nevertheless, it is conceivable that the concept is similar to ‘ecosystem services’ as defined in the academic literature (Costanza et al., 2017) or similar to ‘co-benefits’ defined by the Queensland Government’s Land Restoration Fund (LRF).

6.1 Ecosystems services valuation

The concept of ‘ecosystem services’ includes human-centric benefits derived from ecosystems, either directly or indirectly (Costanza et al., 2017). Ecosystem services may be regulating services (e.g., climate regulation, water quality regulation, pollination, pest control), provisioning services (food production, raw material provision, genetic resources), or cultural services (e.g., recreational opportunities, education or spiritual connection) (Boerema et al., 2017; Costanza et al., 2017). There is inconsistency in how ecosystem services are defined and measured scientifically (Boldy et al., 2021), making it difficult to use ecosystem services for the evaluation of native ecosystem rehabilitation success. It can be assumed that, if a self-sustaining functional native ecosystem is achieved through rehabilitation, then ecosystem services are being provided by nature itself and are not an additional environmental benefit. There may be value in attempting to quantify the cultural and provisioning services provided by the ecosystem where these are explicitly linked to a rehabilitation goal associated with the native ecosystem (Section 6.2). However, quantifying ecosystem services is complex; robust indicators do not exist for all services (Boerema et al., 2017). We discuss below the few methods that do measure ecosystem services (as co-benefits) and are certified by the Accounting for Nature (AfN) organisation (Section 6.3).

6.2 Environmental benefits in *planned novel* ecosystems

Planned novel native ecosystems may be designed to deliver ecosystem services. These may overlap with other defined PMLUs, such as recreational use or forestry. Whilst socio-economic and cultural ecosystem services are beneficial environmental outcomes, they are beyond the scope of this document. There would be value in further exploring the legislative definition of 'beneficial environmental outcomes', particularly in relation to the concept of ecosystem services. There are many existing frameworks for defining, measuring and assessing the outcome of ecosystem services (Bastian et al., 2012; Brown et al., 2014; Díaz et al., 2015; Queensland Government, 2021; Coyne et al., 2022), and some of these have developed in the mine rehabilitation context (Rosa et al., 2018, 2020). For example, carbon farming utilises the CO_2 Australia Native Vegetation Econd Method (available upon request from AfN). These frameworks have been a useful approach to engage communities and link social and ecological outcomes.

6.3 Accounting for Nature Econd score

Accounting for Nature (AfN) is a corporation that reviews methods for assessing environmental condition and provides certification for methods that are scientifically rigorous. For each method, AfN applies an Econd score which standardises environmental condition indices to a score for a particular area (Accounting for Nature ®, 2022). The Queensland Government's Land Restoration Fund (LRF) uses the AfN framework for measuring the condition of environmental assets and verifying environmental outcomes that could be recognised under a co-benefits scheme. Two AfN accredited methods that measure soil and native vegetation condition may have transferability when assessing native ecosystem mine rehabilitation condition, the Soil Health Monitoring Method (SHMM) (Queensland Government Department of Environment & Science, 2020) and the Native Vegetation Condition Monitoring Method (NVCMM) (Butler and Queensland Government Department of Environment & Science, 2020). The SHMM focuses only on soil function and resilience and could be a useful indicator for the soils underpinning ecosystems in mine rehabilitation. The NVCMM is a more ecosystem-focused assessment methodology. It is the Queensland government's BioCondition method (Eyre et al., 2015) (see Section 5) with a few modifications to calculations of indicators, to align with the AfN's Econd scores (Accounting for Nature ®, 2022). These modified indicators make this version of the BioCondition method applicable to mine rehabilitation, as they do not use reference or target REs for comparison, and instead calculate an area-weighted average that can be compared using the same plots over time.

The LRF SHMM (Queensland Government Department of Environment & Science 2020; Table A1-1) method may be applicable to evaluating the success of native ecosystem mine rehabilitation. It was developed in the context of carbon farming projects and is designed to measure the soil 'health' in terms of function/productivity, resilience to acidification, erosion, salinity and physical structure. Additionally, the method outlines approaches facilitating comparison of condition scores to reference soil benchmarks. However, finding an undegraded reference soil can be challenging (Queensland Government Department of Environment & Science, 2020). The LRF SHMM requires access to laboratory facilities and expertise to interpret results. Nevertheless, it is a more robust measure of soil stability and health than the superficial measures used in LFA (Table A3-1).

6.3.1 Co-benefits

The LRF (Queensland Government, 2021) defines co-benefits as the positive environmental, socio-economic and First Nations benefits that arise from a carbon offset project in addition to greenhouse gas abatement. Co-benefits were described in the context of carbon farming initiatives in agricultural systems. Specifically, a change in land use or management is expected to increase carbon sequestration, as well as co-benefits. To be certified as a co-benefit under this framework, evidence must be given for an improvement in condition of the environmental asset. Environmental assets can be classed as Great Barrier Reef catchment, wetland or coastal ecosystems, habitat for threatened ecosystems or species, or, more generally, any improvement in soil or native vegetation condition that can be assessed (Table 3).

The LRF co-benefits concept might be adopted for evaluating native ecosystem mine rehabilitation in cases where delivery of a beneficial environmental outcome is required (e.g., in *hybrid* and *novel* ecosystems). In addition to improved native vegetation condition (which in itself may be set as a criterium for successful mine rehabilitation), the LRF specifies an improvement in soil condition, soils that sequester carbon. This may be considered an 'environmental benefit' when addressing mine rehabilitation and methods that measure increase in soil carbon can be readily applied in that context (e.g., Sanderman et al., 2011). Additionally, there are other ways in which soils can 'improve' in the context of mine rehabilitation and may have benefits on a regional scale. For example, improved soil structure will help mitigate sediment load and erosion, increase bio-available nutrient and plant-available water holding capacity, and help improve regional-scale biodiversity and productivity. Some methods for measuring these metrics are outlined within the SHMM (Queensland Government Department of Environment & Science, 2020).

The other environmental asset classes (Great Barrier Reef catchment, wetland or coastal ecosystems, habitat for threatened ecosystems or species; Table 3) will need tailored methods for each mine that targets, or have existing, *novel* or *hybrid* native ecosystems. This is because they will not fit into the existing RE framework and each of these co-benefits has a broader landscape-scale structure compared to the existing regulatory requirements that are based on site-scale (or at best, regional-scale) assessment. Nevertheless, there is merit to using the existing co-benefit structure as a launching-pad for measuring beneficial environmental outcomes for mine rehabilitation.

Table 3. Environmental co-benefits, class and eligibility as defined by the Queensland Government's Land Restoration Fund (LRF) for the Carbon Farming Initiative and where to find them within the Co-benefit Standard document (Queensland Government 2021). The benefits to society are inferred by authors of this document (SN, CS).

Environmental co-benefit class	Eligibility	Standard section (page)	Benefit to society
Soil Health	verified improvement to soil condition	4.3.1 (11)	Carbon sequestration, biodiversity conservation
The Great Barrier Reef	a) a verified improvement to native vegetation in pre-clearing wetlands in a Great Barrier Reef catchment **or** b) a verified improvement to both native vegetation condition and soil condition within a reef catchment that has a sediment target in the Reef Water Quality Improvement Plan.	4.3.2 (11)	Water resources, biodiversity conservation
Wetlands	a) a verified improvement to the condition of wetland native vegetation **or** b) a verified improvement to the condition of non-wetland vegetation and soil within 100m of a wetland in an Aquatic Conservation Assessment (Queensland Government, 2021) rated as natural or near natural, and as of high or very high significance.	4.3.3 (11)	Water resources, biodiversity conservation
Coastal ecosystems	To claim a Coastal Ecosystem co-benefit, projects must result in a verified improvement to native vegetation condition in coastal REs. Coastal REs are pre-clearing REs on land zones 1, 2 or 3 in a coastal sub-bioregion	4.3.4 (12)	Biodiversity conservation
Threatened ecosystems	a) a verified improvement to native vegetation condition in an RE having the biodiversity status "of-concern" or "endangered" **or** b) a verified improvement to native vegetation condition in an RE listed as containing threatened ecological communities under the *Environment Protection and Biodiversity Conservation Act 1999*	4.3.5 (12)	Biodiversity conservation

Environmental co-benefit class	Eligibility	Standard section (page)	Benefit to society
	(EPBC Act).		
Threatened wildlife	a) a verified improvement to native vegetation condition within areas that meet the definitions of matters of state environmental significance (MSES) for wildlife habitat or matters of national environmental significance (MNES) for threatened species **or** b) a verified improvement to native vegetation condition of REs that are potential habitat for threatened species other than highly mobile fauna.	4.3.6 (13)	Biodiversity conservation
Native vegetation	verified improvement to native vegetation condition	4.3.7 (13)	Carbon sequestration, biodiversity conservation

7 Landscape Function Analysis and Ecosystem Function Analysis

7.1 Definitions

Landscape Function Analysis (LFA) is a soil condition monitoring procedure developed by CSIRO in the 1990s to assess the biogeochemical functioning of landscapes (Tongway and Hindley, 2004). It was developed for use in rangelands and later adapted to monitoring soil surface condition in post-mining landscapes. In recognition of the functional role that vegetation plays in landscape health, the LFA method was expanded to include assessment of vegetation structure and composition, as well as habitat complexity (Tongway and Hindley, 2004). This extended LFA is known as EFA (Lacy et al., 2008) although the terms LFA and EFA are sometimes used interchangeably (RN Humphries, 2016b; Tolentino et al., 2019). In this technical paper we use the term LFA to refer to the core methods of soil condition, surface hydrology and nutrient cycling, and we use the term EFA to refer to the expanded LFA method. We note that the assessment of vegetation structure and composition and habitat complexity are described in more detail (and therefore, may be more appropriate) for other methods we discuss (at QBEIS, Section 4 and BioCondition, Section 5), compared to EFA.

7.2 LFA Measures

LFA soil and surface condition assessments measure the function of an ecosystem in terms of resource use and recycling. A system with high functionality retains vital resources (e.g., water, topsoil, organic matter), in contrast to dysfunctional systems where some of these resources are lost (Tongway and Hindley, 2004). Successful rehabilitation equates to a gain in ecosystem function, i.e., a reduction in resource loss from the system. EFA assesses soil condition, surface hydrology and nutrient cycling to evaluate resource loss; these are proxies for ecosystem function. Vegetation is assessed from the perspective of regulating vital resources (e.g., groundcover protects against wind and water forces), and habitat complexity indices are derived from measures of forest features that promote fauna food and shelter.

7.3 LFA is not applicable for assessing success in mine rehabilitation

LFA is an effective tool for assessing the overall biophysical characteristics of a site (Tongway and Ludwig, 2006). However, in some cases, the trajectory of the floristic assemblage and structural development of the ecosystem are at odds with the measure of condition provided by various LFA indices (Tongway and Hindley, 2004). This discrepancy tends to depend on the age of the rehabilitation. Changes in function during the early stages of *natural* ecosystem rehabilitation correlate with LFA indices scores. However, LFA indices tend to plateau once soil structure has stabilised and vegetation cover has maximised (i.e., follows a sigmoidal pattern over time; Tongway and Hindley 2004). Once a plateau has been reached, LFA indices are less indicative of ecosystem function. Therefore, later stages of rehabilitation will benefit from additional floristic data that reflect different aspects of ecosystem functioning (e.g., recruitment of dominant species). Resultantly, we do not recommend the use of LFA to measure mine rehabilitation success when compared to native ecosystems, *per se*, but the method may still be informative for early monitoring of rehabilitation.

7.4 Ecosystem Function Analysis

Ecosystem Function Analysis (EFA), the extended version of LFA, which includes assessment of vegetation structure and composition and habitat complexity indices, does not account for species identity. This may produce misleading results (Gould, 2012) because EFA does not accurately capture whether a *hybrid* or *novel* ecosystem is a native ecosystem PMLU, dominated by native species. For example, rehabilitation sites being established for a native PMLU may obtain strong scores under EFA indices but be dominated by non-native invasive species (Aspect Ecology Pty Ltd *unpublished data*) or non-target native species (Gould, 2012; RN Humphries, 2016a). Vegetation condition is another important measure of the biodiversity value of ecosystems that is not currently incorporated into EFA (RN Humphries, 2016b).

8 Overall recommendations and conclusion

Rehabilitation may produce *natural*, *hybrid* or *novel* classes of native ecosystems. In each case, appropriate methodologies for evaluating rehabilitation success are required. As the base survey method for all classes of ecosystem rehabilitation, we recommend using the QBEIS site data collection method, optionally at different levels of detail depending on the ecosystem class (Table 4) (Neldner et al., 2022).

The appropriate choice of reference sites is critical when assessing native ecosystem mine rehabilitation for *natural* ecosystems (Appendix 2). Special consideration as to what constitutes a self-sustaining, functional ecosystem is needed when choosing benchmark values for *hybrid* and *novel* ecosystems. It may add value to pair general benchmarks for *novel* ecosystems with monitoring data that tracked the trajectory of the ecosystem development.

It is recognised that different mining operations will have varying measures of rehabilitation success. Moreover, mine operations may have particular objectives for their rehabilitation, depending on such factors as biophysical limitations, stakeholder priorities and incorporation of multi-use PLMU objectives. This may be the case, for example, where *hybrid* rehabilitation is retained as habitat for a specific threatened fauna species, or where *planned novel* rehabilitation provides specific, desired ecosystem services. Therefore, additional methodologies, or modifications to those aforementioned, may need to be employed. Specialised methodologies, oriented towards measuring particular ecosystem services (including “beneficial environmental outcomes” or “co-benefits”) may be used to evaluate the success of *hybrid* or *novel* ecosystems.

Table 4. Recommended methods to evaluate indicators of success of mine rehabilitation to different native ecosystem classes.

Native ecosystem class	Native floristics	Similarity to RE	Environmental benefits	Benchmarking
Natural	n/a	QBEIS[1] secondary site level	n/a	Compare to target RE
Hybrid	QBEIS[1] tertiary[2] site level	QBEIS[1] secondary[3] site level	E.g., SHMM[4] or LRF co-benefits standard[5]	Compare to similar REs using general structural and compositional data only. May need to average benchmark values.[6]
Novel	QBEIS[1] tertiary site level	n/a	E.g., SHMM[4] or LRF co-benefits standard[5]	Compare to similar REs using general structural and compositional data only. May need to average benchmark values.[6]

[1] QBEIS: Queensland Biodiversity and Ecology Information System; see Appendix 1, Table A1-1 for information on site levels.
[2] Only tertiary site level detail is needed if *hybrid* ecosystems are to be managed to maintain novel aspects.
[3] Secondary site level detail is needed if *hybrid* ecosystems are to be managed to become similar to existing RE(s).
[4] Soil Health Monitoring Method (Queensland Government Department of Environment & Science, 2020)
[5] Land Restoration Fund co-benefits standard (Queensland Government, 2021)
[6] See Appendix 2A2.4 for more details.

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Appendix 1 Description of Key Metrics in QBEIS

A1.1 Vegetation Layer Stratification

Vegetation is usually organised into layers, or strata. In Australia, height, cover and life form of the predominant layer are used in the standard vegetation structural classification schemes (Neldner et al., 2022). Stratification could be considered to be the key first step in assessing vegetation, as the determination of layers often affects how other data is collected. Therefore, any assessment of native vegetation, including rehabilitation for *novel* and *hybrid* ecosystems, should categorise strata. In younger rehabilitation, layers have often not yet developed, or are indistinct. However, using knowledge of species composition and abundance, inferences can be made regarding the future structural development of the community. This serves as another reason why species compositions should be recorded as part of monitoring.

A1.2 Species composition

QBEIS Primary and Secondary sites are regarded as particularly suitable to monitor *natural* ecosystem rehabilitation (or *hybrid* rehabilitation being managed towards this state) as they capture a full floristic inventory. This species composition component has been highlighted as a priority for biodiversity measurement in mine rehabilitation (Lloyd et al., 2002). Methods such as BioCondition (Section 5) do measure species richness, but this metric falls short as a lone measure of biodiversity, as it does not record the identity of species. The composition of the establishing and developing rehabilitation is a key descriptor of the ecosystem and forms the basis of whether the mine rehabilitation objectives are being achieved, as well as enabling comparison to the target RE. Thus, this metric has been highlighted as a priority for incorporation into native ecosystem rehabilitation success criteria (Herath et al., 2009). Whilst capture of a full floristic inventory is recommended as leading practice for *natural* ecosystem rehabilitation, in certain circumstances for *hybrid* or *novel* ecosystems recording of woody species and the dominant or conspicuous species in the ground layer may be sufficient, as these ecosystems do not have an RE analogue. Such a level of detail corresponds to a QBEIS Tertiary site (see Table A1-1), and would generally only be necessary where the assessors do not have the skills to compile a complete floristic inventory of non-woody vegetation (Neldner et al., 2022). Whilst a full floristic inventory may not be necessary to measure success of *novel* ecosystems (or hybrid ecosystems being retained in that state), such data may be useful for ongoing management, such as exotic species control.

A1.3 Plant cover

Plant cover is an important ecological feature to be captured within rehabilitation sites (Zine et al., 2021), as it is a long-term indicator of ecosystem development and appropriate for annual monitoring (Herrick et al., 2009). There are several methods which may be used to estimate crown cover of species or strata. Several are described in Neldner et al. (2022), and the preferred method for estimating tree cover is the crown or line-intercept method. Another option, described in Neldner et al. (2022), is the point intercept method, and is particularly appropriate when employed using a vertical densitometer. This method is considered one of the most objective ways to sample cover rehabilitation (Bonham, 2013). This rapid, repeatable and accurate method produces estimate cover values with minimal bias and error (Herrick et al., 2009; Karan, 2015). It is particularly advantageous as no calculation of cover estimates are required: the observer only needs to decide what category of cover type a given point intercepts (Caratti, 2006). Sub-sampling, using a number of small quadrats, is the preferred method for measuring ground layer cover in the QBEIS site data collection method (Neldner et al., 2022).

A1.4 Stem density

Woody species density (the number of stems per hectare) is fundamental to informing current and future vegetation structure in rehabilitation. Stem density measures are almost always used in monitoring where rehabilitation forest or woodland is the land use objective, since this metric must be analysed in relation to establishment rates, mortality, structure and similarity to analogues, all of which are key to understanding performance. Tree density data from analogue sites may also be used to determine the proportions of tubestock (or seed) that must be planted as part of supplementary works. For woodland and forest rehabilitation, the successful establishment and survival of tree seedlings is the single most important indicator that young rehabilitation is on a trajectory towards ecosystem success. Density also gives a quantitative estimate of mortality over time, which is not the case if just cover is used. At Secondary sites a stem count total is recorded (by species), whereas in Primary sites, all woody individuals are tagged, so the count is yielded in that manner. In both cases, the count can be converted to stems/ha using the stem density plot area (Neldner et al., 2022). It is noted in Neldner et al. (2022) that a pragmatic approach is required to measure stem density, particularly for shrubs. Here, we recommend a subsampling procedure be employed for certain species where total count of all stems across the plot is impractical.

A1.5 Tree height and basal area

Basal area and tree height are important metrics for mature rehabilitation, although they may not be considered mandatory at all sites. Basal area (average stem diameter per area) is a highly informative metric because it plays a critical role in development of habitat and therefore in meeting land use objectives. In detailed repeat-monitoring of sites (using the Primary site type), all stems above a certain height (e.g., 2 m) may be surveyed. For once-off monitoring, or for a rehabilitation area in a less-detailed site, basal area may be estimated using a Bitterlich stick or basal area gauge (Neldner et al., 2022), or potentially omitted. As a diagnostic parameter for determining woodland type (Hnatiuk et al., 2009b), tree height should be measured to determine if vegetation analogous to local references has been achieved in the rehabilitation. For mine rehabilitation, the heights of all trees could be measured, or alternatively just a sample from each stratum, depending on the level of detail required.

A1.6 Omissions and modifications for mine rehabilitation

It is noted that many of the landform element attributes in the QBEIS classification set will not be relevant in an anthropogenic mine rehabilitation context. In addition, new designations will need to be derived to cover the post-mining landforms (although it is noted that natural landforms types are now being achieved; Hancock et al., 2020). The QBEIS method also lacks explicit integration of concepts relating to ecological condition. However, the metrics in the QBEIS site data collection method are suitable for assessment of ecological condition, and in addition enable capture of a few other components (e.g., coarse woody debris, habitat features including stag trees or nest boxes, and landform element attributes) to cover the post-mining landforms. Such landforms include pits, “bread loaf” dumps, and the undulating landforms that remain after strip mining. Protocols should be introduced to specify the most analogous natural landform element to the anthropogenic landform. It is worth noting that a few of these additional metrics are captured as part of BioCondition monitoring (see Section 5).

Table A1-1. Survey levels within the QBEIS site data collection method and their potential application to mine rehabilitation monitoring

Site Type[1]	Sample Unit	Distinguishing Aspect	Characterisation Level	Mine Rehabilitation	
				Application	**Recommended Additions**
Quaternary	Point-based	Record of field traverses and to verify/inform vegetation mapping.	Rapid, qualitative/estimate	• Verify/inform rehabilitation mapping • Rapid rehabilitation characterisation	• Add categories important to native ecosystem success (e.g., weed or canopy species abundance)
Tertiary	Plot-based	Used where a full assessment of species is impractical, or assessors do not have the skills	Generally, only the dominant or conspicuous species of the ground layer cover and all woody species are recorded.	• *Novel* ecosystem rehabilitation, or *hybrid* rehabilitation being retained in that state	• Measure for specific 'beneficial environmental outcomes' where the *hybrid* or *novel* ecosystem is considered "not consistent with the use of the land prior to mining"[2] •Stem density (standardly only included in Secondary sites)
Secondary	Plot-based	Classification and detailed descriptions of REs, including identifying all species in vegetation communities.	Individual tree and shrub species **not** marked and tagged or permanently located.	• Annual Monitoring of *natural* ecosystem rehabilitation, and *hybrid* being managed to a *natural* state • Optionally, rehabilitation being retained as *novel* or *hybrid* rehabilitation, where a higher level of site detail is desired/required	• Addition of BioCondition attributes, especially coarse woody debris • Supplement attribute categories (e.g., landform element designations) • Density/presence of stags (standing dead trees emplaced at the earthworks stage) and/or nest boxes.
Primary	Plot-based	The growth of individual plants can be monitored over time.	Individual tree and shrub species **are** marked and tagged or permanently located.	• Repeat site monitoring of *natural* ecosystem rehabilitation	• As per Secondary

[1] Analogue sites should have site type of greater or equal detail level as to that utilised for assessment of the mine rehabilitation.
[2] Environmental Protection Regulation 2019 Schedule 8A.

Appendix 2 Analogue sites and benchmarking against references

An analogue site is one that is self-sustaining and has the attributes of the desired rehabilitation endpoint (Bell, 2001; Tongway and Hindley, 2003). Note that the term "homologue" would be used to specify a landscape that would be replicated in every respect (Tongway and Hindley, 2003), which may be rarely achievable in mine rehabilitation. The comparison of reference systems facilitates the evaluation of restoration success (Suding, 2011; Humphries, 2015; Derhé et al., 2016). Evaluation of rehabilitation success requires determining if the ecosystem components are similar to, or are on a similar successional trajectory toward, a desired endpoint (Chambers et al., 1994; Doley and Audet, 2013). Thus, natural ecosystems are valuable reference systems to evaluate general successional trajectories, and to track the emergence of analogous ecosystem features (Tischew et al., 2014). These ecosystem references should be from the surrounding landscape where available (Vickers et al., 2012; Tischew et al., 2014; Humphries, 2015), but may be selected from further afield (Lundholm and Richardson, 2010). Reference sites are often prerequisite for quantitative evaluation of ecological rehabilitation efforts (Kollmann et al., 2016). Reference or analogue sites have long been utilised in rehabilitation monitoring in Queensland and their use has been recommended by relevant State government agencies (Nichols, 2004). Here we present a general section on relevant considerations when choosing a reference site for the above.

A2.1 Sampling and replication

Achieving the objective of establishing rehabilitation that is similar to the local ecosystems requires a correctly designed and executed analogue monitoring program. This should generate datasets that adequately encompass ecological variation, using a sampling methodology that takes into account resolution, extent and temporal considerations (White and Walker, 1997; Humphries, 2015) and avoids spatial autocorrelations (Legendre, 1993). Importantly, ecosystem references generally provide more of a guide than a strict template for determining current management action (Hulvey et al., 2013). Replication of reference sites is essential to account for the variation that exists within the targeted ecosystem (Ruiz-Jaen and Aide, 2005). A sufficient number of replicated reference sites need to be selected (Eyre et al., 2017). A good example is the Vegetation Condition Benchmarks used for the NSW Biodiversity Assessment Method (BAM); BAM benchmarks were created using a "more-is-better" approach with respect to sites, and also took into account seasonal variability (Yen et al., 2019). In this way, data from analogue sites forms part of the monitoring procedure through time, so that varying seasonal conditions result in a "band" of values to act as targets for rehabilitation (Tongway and Hindley, 2003; Loch and Lowe, 2008).

A2.2 Target type and site selection

The search for habitat analogues is fundamental to efforts to encourage native biodiversity in anthropogenic landscapes (Lundholm and Richardson, 2010). Reference sites need to be selected in a systematic manner, with due regard to the context of the comparisons being made (RN Humphries, 2016a). In general, analogue sites would have similar landscape conditions (soil, slope, position in the landscape, geology etc.), resource regulation, disturbance history and vegetation species to the (existing or targeted) mature rehabilitation (Tongway and Hindley, 2003; Neldner et al., 2022). The location of reference sites may be selected for each of the vegetation and topographical types relevant to a mine's rehabilitation (Grant, 2006; Koch, 2007; Herath et al., 2009; Vickers et al., 2012). In some instances, only a subset of these characteristics will be available at a given site, which highlights the need for replication and targeting within a band of variance. Protocols for selecting and positioning sites can be found in Hnatiuk et al. (2009a).

Neldner et al. (2022) recommends sites be generally selected where there is no evidence of clearing of the predominant canopy evident on the aerial photograph archive or in the field. For rehabilitation communities, Gravina et al. (2011) emphasise that careful consideration is needed when comparing immature areas with mature analogues. Humphries (2015) suggests that structurally immature rehabilitation sites should be compared with structurally immature references, so long as the dominant species of the target ecosystem characterise the analogue sites. We suggest that suitable immature analogue sites areas may include vegetation that has been "pulled", but either allowed to regrow or, where the understory and/or 'bud bank' is intact. Such areas include those cleared in preparation for mining but never (or not yet) mined, and regrowth vegetation cleared for pastureland but never seeded with exotic pasture species (C. Spain pers. obs.). Such an approach seems to be little used (Humphries, 2015), and further research is needed regarding the parameters of its valid application, such as types of suitable regrowth and when analogue targets should be switched to mature references.

A2.3 Application to natural ecosystems

Where rehabilitation targets a *natural* state, analogue sites should always be used. Ecological references identify the particular terrestrial ecosystem that informs the target of the restoration project (Standards Reference Group SERA, 2021). The use of reference data is important in establishing *natural* rehabilitation as it facilitates determination of conditions under which restored ecosystems are likely to be self-sustaining (White and Walker, 1997). Reference ecosystem plot data can be used to derive quantitative targets for restoring native communities on mined land (Erskine et al., 2019). The success of rehabilitation targeting an *historical* ecosystem can be gauged by the level of structural and floristic similarity to surrounding intact natural examples of the community (van Aarde et al., 1996). Under leading practice, target REs will be specified within the initial mine Progressive Rehabilitation and Closure plans (PRC plans) for *natural* ecosystem rehabilitation. For mine projects establishing in areas currently occupied by remnant vegetation, there are often extensive opportunities for capturing analogue site data pre-clearing. This data will be especially valuable where the target of rehabilitation is the *historical* ecosystem itself. Consideration should be given to the fact that, once the remnant vegetation is removed, the sites cannot be revisited and therefore strategic and accurate data capture is paramount.

A2.4 Application to *novel* and *hybrid* ecosystems

Adopting *novel* or *hybrid* ecosystems as targets for severely degraded post-mining landscapes is problematic since, by definition, such systems lack analogues to provide the baseline or reference conditions (Gwenzi, 2021). Doley and Audet (2013) suggested that, in certain circumstances, a moving away from strict adoption of ecological reference sites and applying the natural-novel ecosystem paradigm are warranted. However, analogue sites still have a role in highly degraded or biophysically limited rehabilitation where *hybrid* or *novel* rehabilitation has become established, or where a *planned novel* ecosystem is the rehabilitation target. For example, we see two main applications:

- in determining/informing if existing rehabilitation is *novel* or *hybrid*, and if the latter, which RE(s) it is most similar to, and
- in serving as a source of data for structural and compositional targets, even though the rehabilitation may not be aiming to (or able to) establish an ecosystem analogous to the reference type(s).

Neldner et al. (2022) recommends that, where it is not possible to find an appropriate local reference site, reference site values (benchmarks for median height and canopy cover) be obtained from published Queensland Herbarium Regional Ecosystem technical descriptions, QBEIS sites, published benchmark descriptions or other published descriptions for the relevant regional ecosystem.

For *hybrid* ecosystem rehabilitation, a specific RE may be an appropriate target where there is sufficient similarity. However, the *hybrid* ecosystem may be part-way between two or more REs, and the choice will need to be made to either select one of them or to derive a benchmark that is an amalgam. This latter approach was the one opted for by Neldner & Ngugi (2014), who developed a new benchmark derived using data from 26 analogue sites from three local eucalypt woodland REs. In Neldner & Ngugi (2014), the amalgam benchmark was useful as the rehabilitation being assessed was to become a woodland. However, amalgams would not be valid where they combine different structural types. Reference site benchmarks, even if they are amalgams, should match the structural formation class target of the rehabilitation (see Table 28 of Neldner et al. 2022) for structural formation classes based on the ecologically dominant layer of the ecosystem). For the survey of non-mature rehabilitation, the structure class thresholds in Table 30 of Neldner et al. (2022) also need to be considered, noting that developing rehabilitation is analogous to unmined regrowth vegetation.

For *novel* ecosystem rehabilitation, the resultant ecosystem may be a completely different structure to the ecosystems in the local area e.g., a shrubland, where there are no shrublands locally occurring. If BioCondition is to be used for assessment of *novel* ecosystem rehabilitation, candidate analogue sites may need to be found further away within the bioregion. Alternatively, a selection of multiple reference ecosystems can be used to inform and manage targets, and to calculate average benchmark values. In this context, suites of reference sites for a particular aspect of structure or function should apply, rather than a representation of what the end-point ecosystem should resemble as a whole. It should be noted that the use of reference sites is this context does not obviate the risks involved in establishing or maintaining *hybrid* or *novel* ecosystems.

A2.5 Data analysis

Simple comparisons of benchmark values between sites (or site averages) can help inform how close rehabilitation sites are to references. Visualisations, like spider-web plots, can also help in the process (e.g., Neldner & Ngugi 2014). Alternatively, more complex statistical clustering analyses can be used as a measure of similarity between ecosystems (e.g., Principal components analysis, correspondence analysis) (Zuur et al., 2007; Peake et al., 2021). This allows for a more probabilistic approach to the data analysis which would allow calculations of confidence intervals and the interpretation of more complex data like species compositions. The difficulty with the latter approach is that is often requires a lot of data and considerations need to be made to systems of differing ages.

Appendix 3 Details of each method for assessing mine rehabilitation success to native ecosystems

Table A3-1. Metrics assessed in each of the discussed field methods for evaluating native ecosystem rehabilitation success. Acronyms: AfN (Accounting for Nature); LRF (Land Restoration Fund); RE (Regional Ecosystem); OMC (organic matter content); EC (electrical conductivity); QBEIS (Queensland Biodiversity and Ecology Information System)

Biophysical aspect	Assessment	QBEIS	Bio-Condition	LRF Native Ecosystem Condition Monitoring Method	Ecosystem Function Analysis	LRF Soil Health Monitoring Method
Calculation of index	Comparison to analogue/reference				✓	✓
	Comparison to RE	✓	✓			
	Area-weighted average			✓		
Landform	Pattern, elements	✓			✓	
Soil	Superficial field description (texture, OMC) or Australian Soil Classification (ASC)	✓	✓ (OMC)	✓ (OMC)	✓ (texture, surface roughness)	
	Detailed physical analysis (bulk density, aggregation)					✓ (bulk density[1])
	Erosion (visible signs of deposition) or erosion risk (ground cover, soil crusting)	✓ (QBEIS database)			✓ (erosion signs and erosion risk)	✓ (ground cover)
	Water infiltration				✓ (rain splash protection, slake test)	
	Nutrient content (nitrogen, phosphorous, carbon, etc)					✓ (C, N[1])
	Chemistry (pH, salinity, phytotoxic chemicals)					✓ (pH, salt-affected area, EC[1])
	Biological activity				✓ (visual inspection of litter decomposition)	

Biophysical aspect	Assessment	QBEIS	Bio-Condition	LRF Native Ecosystem Condition Monitoring Method	Ecosystem Function Analysis	LRF Soil Health Monitoring Method
Vegetation	Structure (strata, biomass, height, density)	✓	✓	✓	✓	
	Richness	✓	✓	✓		
	Composition	✓				
	Non-native richness	✓				
	Non-native structure	✓	✓	✓		
Fauna	Available habitat		✓	✓	✓	
	Grazing index	✓	✓ (distance to permanent water)	✓ (distance to permanent water)		
Landscape context	Connectivity to surrounding landscape	✓ (remnant vegetation extent)	✓	✓		