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Exploring biophysical limitations and post-mining native ecosystem rehabilitation outcomes in Queensland

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Abstract

In Queensland, Australia, 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, non-polluting and able to sustain a post-mining land use (PMLU). 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. It is in this context that the Office of the Queensland Mine Rehabilitation Commissioner is undertaking research to define and understand the drivers for various native ecosystem rehabilitation outcomes and describe best practice with respect to planning for and evaluating the success of native ecosystem PMLUs in Queensland.

In Queensland, rehabilitated ecosystems that develop in highly disturbed landscapes often produce one of the following outcomes: they may be natural (restored to the extent of historic succession trajectory); hybrid (have some but not all characteristics of the natural/historic landscape, and some novel attribute); or novel (a new assemblage of abiotic and biotic attributes resulting in a stable alternative ecological form). This natural–novel paradigm, is a useful tool for evaluating rehabilitation options on mine sites. However, the natural–novel concept is not without controversy or criticism. For example, it raises the question: does accepting ecosystem novelty equate to a 'lowering of the bar' with regards to ecosystem rehabilitation goals? Or, conversely, is ecosystem novelty an opportunity for innovative delivery of ecosystem services in otherwise degraded landscapes? In the present work, we extend on the natural-hybrid-novel framework to include substitute natural ecosystems as a rehabilitation outcome that should be considered when biophysical limitations preclude establishment of the pre-mining natural ecosystem. We also articulate the distinction between planned novel ecosystems (i.e. ecosystems designed to deliver beneficial environmental outcomes) and unplanned novel ecosystems (the inadvertent result of rehabilitation attempts when biophysical limitations preclude natural ecosystem establishment) and suggest that these, and hybrid ecosystems, be evaluated in light of the environmental, biological and human-centric ecosystem services they deliver.

Keywords: *biophysical limitations, ecosystem services, mining, novel ecosystems, rehabilitation, restoration*

1 Native ecosystem rehabilitation in Queensland

Mine rehabilitation is the return of land disturbed by mining to a stable, safe, non-polluting condition that supports a post-mining land use (PMLU) (*Environmental Protection Act 1994, s 111A*; Queensland Government 1994). It differs from the concept of remediation, which focuses only on achieving physical and chemical stability of land (Keenan & Holcombe 2021). Rehabilitation is also distinct from the concept of restoration, which aims to re-instate a pre-disturbance condition, or achieve ecosystem indicators equivalent to those in an unmined target ecosystem (often referred to as a reference site) (Australian Government 2016). PMLUs need to be viable, and they may be consistent with the land use prior to mining, or they may be new land uses that deliver beneficial environmental outcomes (Environmental Protection Regulation

2019; Queensland Government 2019). However, what constitutes a 'beneficial environmental outcome' and how it is definitively measured is not currently articulated in legislation.

Mining fundamentally disturbs the biotic and abiotic conditions on which pre-mining ecosystems are founded, and as a result it is widely accepted that ecosystem restoration is an aspirational rather than attainable goal for rehabilitation of highly disturbed sites (Doley & Audet 2016; Erskine & Fletcher 2013). However, there are examples of ecological restoration at mine sites across Australia that demonstrate that ecosystem restoration is possible, with careful planning and appropriate management intervention (Grant 2006; Peake et al. 2021; Ryba 2021). Some indicators of success in these cases include levels of rehabilitation that have produced ecosystems with species richness, stem densities and management levels similar to surrounding unmined forest, or the return of native fauna in large numbers and diversity (Grant & Koch 2007; Ryba 2021).

Presently in Queensland, Australia, all mines with a site-specific environmental authority are required to develop a Progressive Rehabilitation and Closure (PRC) plan, articulating the rehabilitation milestones and criteria for their site. Native ecosystem is one of the major PMLUs proposed by mining companies in Queensland. However rehabilitation milestone criteria for this broad PMLU vary markedly between sites, with rehabilitation objectives spanning the full spectrum of the natural-hybrid-novel ecosystem concept. For the purposes of this study, we consider native ecosystems to be those dominated or co-dominated by native species. Native species are those identified in the Queensland Plant Census (Brown 2021). For details regarding dominance and composition within Queensland's native ecosystems (refer to Neldner et al. 2019a, 2022).

Selecting and justifying appropriate PMLUs is a critical part of rehabilitation planning. When the PMLU is a native ecosystem it is important to consider the situations where ecosystem restoration (i.e. returning a site to its pre-disturbance condition) is a realistic rehabilitation goal, compared to the delivery of beneficial environmental outcomes via an alternative (e.g. hybrid or novel) native ecosystem outcome. Naturally occurring ecosystems ('regional ecosystems' or REs) within the Queensland framework (Neldner et al. 2019b) are strongly influenced by landform, soils and geology (Neldner et al. 2019a), all of which are disturbed by mining. Thus, when comparing PMLU options during PRC plan development, the administering authority will give regard to factors such as physical and chemical constraints, relative costs of rehabilitation options, potential economic, environmental and social benefits for each option and compatibility with the surrounding land use (Department of Environment and Science 2021), consistent with section 126(1)(j) of the Environmental Protection Act 1994 (Queensland Government 1994). The aim of this paper is to explore the concept of natural versus novel rehabilitated ecosystems in light of the biophysical limitations imposed by mining, with a view to understand what constitutes best practice native ecosystem rehabilitation objectives and measures of success.

2 Rehabilitated native ecosystems: definitions

2.1 Diversity of post-mining native ecosystems

The natural-novel paradigm, as described by Hobbs et al. (2006) and later expanded by Doley & Audet (2013) is a useful tool for understanding native ecosystem rehabilitation on mine sites. The concept is founded on the fact that ecosystem composition, function and stability are all influenced by biophysical conditions (e.g. geology, landform and soils), which are severely (and sometimes irreversibly) disrupted during mining (Doley et al. 2012). At one end of the spectrum, in cases where post-mining soils, landform and hydrological conditions remain suitable or can be made suitable (Lamb et al. 2015) to support the pre-mining RE, a natural ecosystem may be established after mining. The process of assisting recovery of a disturbed ecosystem is often referred to as ecosystem restoration and involves establishing, or setting a trajectory towards the species composition, structure and function of the ecosystem disturbed by mining (Young et al. 2019).

At the other end of the spectrum, where the pre-mining RE is unable to be developed, novel ecosystems may establish which comprise new assemblages of abiotic and biotic attributes resulting in a stable alternative ecological state that does not resemble a natural ecosystem (Doley et al. 2012; Doley & Audet 2013). Novel ecosystems are generally regarded as the unintended result of human alteration of the environment (Hobbs et al. 2013a, 2014a). They are stable, unique ecosystems, characterised by both native and non-native organisms, that often develop in highly disturbed sites and have crossed an irreversible disturbance threshold and cannot be restored to a natural state by management intervention (Doley et al. 2012; Doley & Audet 2013; Erskine & Fletcher 2013), see Table 1.

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	Ecosystem functions are similar to an RE, but ecosystem is characterised by unique attributes that are not found in an RE. These unique aspects can be overcome by management to move the ecosystem towards an 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 an analogous RE. These unique aspects cannot be managed to move the ecosystem towards an RE.	Stable ecological form that cannot be manipulated to become an RE via management intervention.
Novel	Planned	A planned native ecosystem that meets specific ecosystem services objectives but has no RE analogue (i.e. it is intentionally novel). Also known as a designer ecosystem.	Self-sustainability unknown, though expected to require management. Cannot be manipulated to become a RE.

Sitting between natural and novel ecosystems are hybrid ecosystems which have some, but not all, characteristics of the natural landscape, and some novel attributes (Gwenzi 2021; Higgs 2017). They represent a significant deviation from natural ecosystems, for example by the presence of species that would not naturally occur together, but their key ecosystem functions (e.g. nutrient cycling and hydrology) remain largely the same (Clement & Standish 2018; Doley & Audet 2013; Hobbs et al. 2009). 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. 2013a), see Table 1.

2.2 Extensions of the natural-hybrid-novel paradigm

In the context of evaluating native ecosystem rehabilitation outcomes in Queensland, we feel it is timely to expand on the natural-novel continuum with two important variations that might be useful in PMLU planning: substituted ecosystems and planned novel ecosystems (Table 1). Doley & Audet (2013, 2016) defined rehabilitation to a natural ecosystem as synonymous with establishing the pre-disturbance ecosystem (i.e. the pre-disturbance RE). However, this definition is restrictive to a single target RE and does not allow for rehabilitation to another naturally occurring RE which did not exist at the site historically but might be well suited for the present-day post-mining conditions. Here, we expand the definition of natural rehabilitated ecosystems to also include substituted REs. These are in contrast to hybrid and novel ecosystems (Table 1) which do not have an analogue in nature. Substituted REs must be within the site's bioregion, preferentially bioregional subregion (Neldner et al. 2019b) or geographically proximal.

Substituted REs may be an appropriate rehabilitation goal when radical differences between the physicochemical and biological characteristics of the pre-mining versus rehabilitated mine environments preclude restoration of the pre-mining RE (Doley et al. 2012). For example, a pre-mining floodplain-associated RE may not successfully develop on steep post-mining slopes of spoil piles or waste rock dumps that need to be rock armoured to prevent erosion. However, substituting a hill–associated RE from the region may promote more successful outcomes (i.e. the development of a stable, self-sustaining, resilient natural ecosystem) by targeting a species mix that is naturally adapted to the rocky slopes in this post-mining situation (Gillespie et al. 2015). Another example might be in the case of shallow strip mining such as bauxite mining where most of the orebody is removed and the resultant post-mining landscape is lower than that prior to mining. Substitution of an RE that is naturally adapted to the altered post-mining hydrological regime and occurs locally so also suits the local climate (e.g. Melaleuca wetlands rather than a pre-existing eucalypt forest), may be a more realistic target for a sustainable PMLU. Substitute REs as a rehabilitation objective take advantage of the strengths of natural ecosystems that survive and are resilient in landscapes analogous to post-mining landscapes, rather than attempting to re-create pre-mining REs on post-mining landforms, soils or hydrogeologic settings that might not inherently support them.

There are also situations where intentionally created native ecosystems comprising unique biotic and abiotic assemblages (i.e. comprised of native species, but not resembling a naturally occurring RE) may be an appropriate rehabilitation target. Similar to substitute REs, these planned novel ecosystems (Higgs 2017) take into account the biophysical limitations imposed after mining to target a native species mix that best suits the post-mining landforms and hydrogeology. However, unlike substitute REs, the final ecosystem assemblage does not have an analogue in nature. Planned novel ecosystems are goal-oriented, established to meet specific objectives with a primary focus on human interests (Ross et al. 2015), including those that may relate to native ecosystems, such as biodiversity improvement and habitat connectivity (Higgs 2017). Beneficial environmental outcomes that can conceivably be achieved with planned novel ecosystems include, for example, carbon sinks (Pietrzykowski & Daniels 2014; Tripathi et al. 2016) or native seed orchards (Annandale et al. 2021; Gardner & Bell 2007; Nichols et al. 1985). These planned novel ecosystems are distinct from the novel ecosystems described above, which are unplanned and often the unintentional result of rehabilitation attempts towards an RE that were limited by post-mining biophysical conditions. This important distinction will be recognised hereafter by referring to novel ecosystems as either planned novel and unplanned novel ecosystems (Table 1). Even though planned novel ecosystems are intentionally designed to deliver a specific beneficial outcome, it is important to note that they are not necessarily self-sustaining ecosystems and may require management at levels higher than natural systems (Higgs 2017).

3 Biophysical limitations and feasibility of native ecosystem rehabilitation outcomes

Every mine site has unique hydrological, landform, geochemical and biological (i.e. biophysical) conditions that influence the type of native ecosystem (e.g. natural, hybrid or novel, see Table 1) that can be practicably achieved from rehabilitation efforts. It is important that these biophysical limitations are appropriately assessed at each site, to ensure that ecosystem rehabilitation targets are realistic and achievable, and appropriate management intervention can be made to ensure that the final PMLU delivers beneficial environmental outcomes (Environmental Protection Regulation 2019, Queensland Government 2019). Table 2 summarises key biophysical limitations that need to be considered during native ecosystem rehabilitation planning and provides examples of best practice methods for rehabilitation to maximise delivery of beneficial environmental outcomes. We acknowledge that this list of best practice methods is not exhaustive, and we welcome new and scientifically tested rehabilitation techniques and technologies. Aspects relating to best practice methods, could underpin development of closure criteria to monitor ecosystem rehabilitation progress. Further information relating to qualitative and quantitative rehabilitation milestones and criteria can also be found in Table 2.6 of Young et al. (2019). The implications for which native ecosystem class (i.e. natural, hybrid or novel) can be targeted given biophysical limitations, is also summarised in Table 2.

Table 2 Biophysical limitations, their consequences and management practices that influence native ecosystem rehabilitation outcomes

Biophysical limitation	Consequence	Methods for maximised delivery of beneficial environmental outcomes	Implications for native ecosystem class
Landform characteristics (slope, stability)	Steep landform slopes provide an altered hydrologic regime, and/or an increased risk of surface subsidence or erosion gullies.	Geomorphic landform design principles and long-term erosion models informed by on-ground data (Hancock et al. 2019; Howard et al. 2011).	Reshaping landforms to enable pre-mining RE establishment is preferred. Where this is not possible due to space constraints, altered hydrology of the post-mining landform may mean a substitute RE is a more feasible rehabilitation target than historical RE.
Physicochemical and biological properties of growth medium	• Substrate may be acidic, alkaline, sodic, saline, nutrient-limited and/or have high levels of heavy metals that limit plant growth. • Highly sodic material may be susceptible to erosion. • Poor soil structure may lead to reduced water holding capacity and water stress for establishing plants. • Low microbial activity affects soil nutrient and carbon cycling and plant health.	• Undertake full suite of soil chemical analyses to assess nutrient toxicities and limitations and amend growth medium with organic matter, gypsum and/or any relevant trace metals as informed by soil chemistry data (Dale et al. 2018). • Use of fresh topsoil or biologically active amendments to promote microbial activity.	• Without addressing growth medium limitations, the rehabilitated native ecosystem is at risk of being a hybrid system requiring ongoing management, or of becoming an unplanned novel ecosystem. • Substitute RE or planned novel ecosystems may be desired targets when growth medium cannot be easily amended (e.g. a salt-tolerant RE in saline post-mining soils). • Hybrid ecosystems that contain species that tolerate initial post-mining conditions (e.g. low nutrients, altered pH) can facilitate initial plant establishment, while retaining the option for future management to an RE. • Planned novel ecosystems may be targeted if toxic material remains after best practice rehabilitation methods.

Biophysical limitation	Consequence	Methods for maximised delivery of beneficial environmental outcomes	Implications for native ecosystem class
Current and future climatic conditions	Extreme temperatures and rainfall conditions limit seed germination and plant establishment.	• Select planting at the time of year or during years that have optimal conditions for plant growth (Gillespie et al. 2015; Schwenke et al. 2000). • Select propagules collected from provenances with more extreme climatic conditions (if available for species found across different climatic zones) to help the developing rehabilitation to adapt to climate change (Prober et al. 2015).	• Climate will affect successful establishment of all planned ecosystems. Multiple plantings may be required to ensure desired species mix is achieved. • Potentially planned novel ecosystems that are adapted to climate change might be considered.
Availability, viability and competitiveness of native seedbank	Competition from non-native species limits native establishment and can alter successional trajectory of desired native species.	• Early effort on successful initial establishment of native species from topsoil seedbank, broadcast seeds and/or tubestock planting. • Limit use of fertilisers. • Weed control to suppress non-natives that germinate from the topsoil seedbank (Cole et al. 2006; Grant & Koch 2007; Ryba 2021).	Direct placement of topsoil is best practice for establishment of historical RE as it leverages the viable natural seedbank. For establishment of all other ecosystem types, or for topsoil that has been stored, seeding and/or tubestock planting, combined with targeted weed control is essential.
Availability and suitability of fauna habitats	Delay in ecological services from fauna (pollination, seed and spore dispersal, vegetation regulation).	• Installation of habitat structures e.g. woody debris and nest boxes. • Connect rehabilitated ecosystem to existing native ecosystems to allow for habitat corridors (Grant & Koch 2007; Ryba 2021).	The function of all ecosystem classes will benefit from the installation of habitat structures. Connecting rehabilitated natural ecosystems to existing native ecosystem is best practice. However, hybrid and novel ecosystems will need ongoing management to ensure they are not a source of weeds to connected natural ecosystems.

4 Best practice native ecosystem rehabilitation outcomes

In considering what constitutes best practice when comparing native ecosystem rehabilitation outcomes in Queensland we note that PMLUs must be viable, and they may be consistent with the land use prior to mining (i.e. rehabilitation of the natural RE, see Table 1) or they may be new land uses (i.e. substitute REs, hybrid or novel ecosystems) that deliver beneficial environmental outcomes (Environmental Protection Regulation 2019, Queensland Government 2019). Determining the viability of a proposed native ecosystem rehabilitation outcome is important during rehabilitation planning and is underpinned by consideration of biophysical limitations at the site (Table 2). REs are strongly influenced by landform, geology and soils (Neldner et al. 2019a). Therefore, addressing the biophysical limitations that might hinder RE establishment (see 'Methods for maximised delivery of beneficial environmental outcomes' in Table 2) is important before commencement and during on-ground rehabilitation works, to ensure that the target ecosystem is a viable rehabilitation objective.

Where biophysical limitations are likely to preclude rehabilitation of the pre-mining RE, alternative ecosystem types may be more viable rehabilitation targets. For example, where post-mining landform reshaping to a pre-mining state is not possible, potentially due to insufficient material or space to extend and flatten slopes, substituted ecosystems that exist in the bioregion on analogous landforms, offer a viable alternative. Where biophysical limitations are not able to be overcome by rehabilitation actions ('Methods for maximised delivery of beneficial environmental outcomes' in Table 2), planned novel ecosystems are a preferred rehabilitation target, rather than allowing the development of unplanned novel ecosystems in response to the biophysical limitations. Planned novel ecosystems (Table 1) present an opportunity to incorporate the concept of 'beneficial environmental outcomes' into PMLU planning as they are designed to meet specific objectives with a primary focus on human interests (Higgs 2017; Ross et al. 2015).

While 'beneficial environmental outcomes' are not defined in legislation, it is conceivable that the concept might be similar to the concept of ecosystem services as defined in the academic literature. Ecosystem services are "those processes and functions that benefit people, consciously or unconsciously, directly or indirectly" (Costanza et al. 2017). Ecosystem services include physicochemical environmental aspects (erosion control, gas regulation, water regulation, soil formation, nutrient cycling) as well as biological functions (refugia, pollination, species interactions) and human-centric services (food and raw materials, genetic material availability, recreational and cultural opportunities) (Costanza et al. 2017).

Some authors have indicated that ecosystem services from rehabilitated ecosystems should be equal to or greater than those provided by *natural* ecosystems (Humphries & Tibbett 2015). This may be an unattainable goal for legacy rehabilitation, or where rehabilitation works have been delayed resulting in biophysical limitations that are now extremely severe. However, there is value in incorporating ecosystem services goals into native ecosystem rehabilitation planning in Queensland to ensure that rehabilitation delivers beneficial environmental outcomes, consistent with the intent for PMLUs in the Environmental Protection Regulation 2019 (Queensland Government 2019). Where explicit ecosystem services goals are not incorporated into rehabilitation planning, and where best practice management approaches to align rehabilitated ecosystem objectives and rehabilitation efforts with biophysical limitations (landform, climate, habitat, weeds, etc., see Table 2) are not undertaken, hybrid or unplanned novel ecosystems will be the inadvertent outcome. These are not considered best practice from the perspective of delivery of beneficial environmental outcomes.

5 Benefits and challenges with adopting alternative ecosystem outcomes

It is recognised that target PMLUs need to avoid exceedingly expensive or protracted maintenance of rehabilitation into the future (Doley et al. 2012). Where both the abiotic and biotic systems are significantly and irreversibly affected by mining, such that rehabilitation to a natural (either historic or substitute, see Table 1) ecosystem is precluded, planned novel ecosystems could represent a viable rehabilitation option (Doley & Audet 2013; Higgs 2017) that offers beneficial environmental outcomes, for example as carbon sinks

(Pietrzykowski & Daniels 2014; Tripathi et al. 2016), native seed orchards (Annandale et al. 2021; Gardner & Bell 2007; Nichols et al. 1985) or for biodiversity improvement (Higgs 2017). However, both creating and managing these non-natural ecosystems may be controversial (Truitt et al. 2015), as some researchers and rehabilitators contend that acceptance will facilitate the degradation of land through less stringent regulation (Aronson et al. 2014; Clewell & Aronson 2013), although this is debated (Hobbs et al. 2014b). It is worth noting that the term 'novel ecosystem' when first introduced, was primarily considered in relation to invasive species (alongside climate change – Hobbs et al. 2013b). Best practice standards need to be established so that adoption of planned novel ecosystems does not result in unnecessary land degradation (Humphries & Tibbett 2015).

In the context of native ecosystem rehabilitation, planned novel ecosystems may facilitate multi-use outcomes while simultaneously bridging the conceptual divide separating the ecological function of re-instated natural landscapes versus derelict and/or unusable landscapes (Doley et al. 2012; Higgs 2017). Therefore, there is excellent potential for planned novel ecosystems as native ecosystem PMLUs. As they are designed to achieve specific outcomes, planned novel ecosystems can place an even greater emphasis on delivery of certain ecosystem functions than their unplanned novel counterparts. They can be explicitly designed to deliver new functions not generally provided by natural ecosystems, or optimised functions, or both (Light et al. 2013).

In contrast, hybrid and unplanned novel ecosystems both have controversial aspects that give rise to questions about their value as proposed PMLUs. However, hybrid and unplanned novel ecosystems are common outcomes from past native ecosystem rehabilitation attempts in Queensland (Doley & Audet 2013; Erskine & Fletcher 2013) therefore they warrant consideration here. By definition (Table 1), hybrid ecosystems are similar to natural ecosystems and the unique aspects that distinguish them from a natural ecosystem can be corrected via management intervention (e.g. weed control, or re-planting under-represented natural species). There are no feasible biophysical barriers to implementing the required management from hybrid to natural ecosystems. Therefore, we suggest a cost-benefit analysis, incorporating existing habitat qualities and ecosystem services, in deciding whether to retain existing hybrid ecosystems. Where the rehabilitation is relatively young, then interventions to target a natural ecosystem (e.g. removal of non-native tree species) are likely beneficial. Alternatively, where the hybrid ecosystem floristics do not closely align with any natural ecosystem, but the trees are large and offer high levels of habitat value or other ecosystem services, then retaining the hybrid state is likely to be preferable.

The situation is somewhat different for unplanned novel ecosystems where, by definition, the rehabilitation cannot be managed into a natural state (Table 1) (although correctly identifying an established ecosystem as novel rather than hybrid can be challenging without first attempting management interventions on the system to evaluate the response). Retaining existing unplanned novel ecosystems may be an acceptable outcome where delivery of ecosystem services can be demonstrated (see section 4 above). Incorporating these unplanned novel ecosystems under the native ecosystem rehabilitation umbrella, recognises that the category may provide opportunities for biodiversity conservation and ecosystem service provision (Perring et al. 2013). It should be noted that the novel ecosystem concept, does not serve as justification to reduce expectations for rehabilitation outcomes (Standish et al. 2013). Rather, it assists land managers in ecological goal setting, to identify what can realistically be accomplished and the magnitude of management intervention required to achieve a desired ecological outcome (Doley & Audet 2016; Wagner et al. 2016).

6 Important non-technical considerations

Thus far we have considered a range of technical and practical considerations that influence which native ecosystem rehabilitation outcomes are viable in light of post-mining biophysical limitations. Where biophysical limitations preclude rehabilitation of a natural ecosystem (either the pre-mining RE, or a substitute RE), we propose that delivery of beneficial environmental outcomes could be demonstrated by the provision of ecosystem services that include environmental, biological and human-centric services (Costanza et al. 2017). This concept is fundamental for planned novel ecosystems but can also be extended to the evaluation of hybrid and unplanned novel ecosystems that have arisen from past rehabilitation practices. However, it is important that evaluation of biophysical limitations and assessment of ecosystem services are not used as a replacement for genuine stakeholder engagement during rehabilitation planning, to determine preferred PMLU outcomes. Furthermore, the type and quality of ecosystem rehabilitation may also have implications for the level of ongoing management required into the future and therefore have economic implications with regard to the residual risk remaining post-mining.

Mining companies accept both rights and responsibilities when granted authority to extract Queensland's mineral resources. Best practice across all phases of the mining lifecycle includes effective stakeholder engagement to ensure that the responsibility expected from those granted mining rights, are given due attention. Stakeholders are those that have a justifiable interest in a project, including government departments, affected landholders, Traditional Owners and local community groups (DES 2021). In Queensland, community engagement is a requisite for a PRC plan, and proposed PMLUs must be derived in consultation with the community (DES 2021). Early stakeholder engagement to arrive at a mutually agreed PMLU is a critical part of effective mine planning. Stakeholders provide insight into the values of the land that matter to them and that they expect will be restored post-mining (Boldy et al. 2021; Everingham et al. 2018). Stakeholders also offer valuable local knowledge that can aid development of completion criteria, and stakeholders can assess rehabilitation performance (Everingham et al. 2018; The Minserve Group Pty Ltd 2007). Early and ongoing stakeholder engagement through all stages of rehabilitation also allows for expectation management regarding what is practically achievable, for example in light of biophysical limitations or technological or regulatory constraints (Australian Government 2016; Ferguson et al. 2021). The framework we have explored here (Tables 1 and 2) is not intended as a substitute for determining stakeholder (regulator and community) acceptability of native ecosystem PMLUs.

7 Conclusion

Presently in Queensland post-mining native ecosystem rehabilitation outcomes are viewed as either natural (i.e. restoration to the pre-mining RE) or unplanned novel (a stable, unique biotic assemblage that developed due to biophysical limitations and is not able to be made similar to an RE). Hybrid ecosystems are similar to novel ecosystems although are still able to be made similar to an RE with management intervention. Therefore, we do not consider hybrid ecosystems a rehabilitation end point, as management intervention to make them natural ecosystems is possible. However, hybrid ecosystems may be a useful intermediate state to overcome initial biophysical limitations.

Biophysical limitations such as landform slope, stability, soil characteristics and availability of a seedbank or fauna habitat affect the type of native ecosystems that may be achievable from rehabilitation efforts. Without appropriate management, such factors drive the development of unplanned novel ecosystems from rehabilitation efforts. To prevent this, early consideration and implementation of best practice management techniques (see Table 2) to produce native ecosystems that deliver beneficial environmental outcomes (see Section 4) is critical. We posit that considering substituted REs where biophysical considerations may preclude establishment of the pre-mining RE, as well as planned novel ecosystems that are designed to deliver ecosystem services despite biophysical limitations, are useful alternatives to consider during rehabilitation planning. Regardless of the biophysical limitations that a site presents, engagement with stakeholders including regulators, Traditional Owners and local community groups that will be affected by the PMLU is fundamental in rehabilitation planning.

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