Office of the **Queensland Mine Rehabilitation Commissioner**

Rehabilitated mined land suitability for beef cattle grazing in the Bowen Basin

Technical paper 1

Queensland Government

Prepared by: Highlands Environmental on behalf of the Office of the Queensland Mine Rehabilitation Commissioner

Citation

Short TA. 2023. Rehabilitated mined land suitability for beef cattle grazing in the Bowen Basin: Technical paper 1. Brisbane: Queensland Mine Rehabilitation Commissioner, Queensland Government.

Acknowledgements

The author thanks Mr George Bourne for his time spent reviewing an early draft of this technical paper, careful reading and insightful comments and suggestions for improvement.

October 2023

Contents

Tables

Executive Summary

Beef cattle grazing is the most common post-mining land use (PMLU) in the Bowen Basin, where coal mining has disturbed more than 170,000 hectares of land. Less than a third of this disturbance has been rehabilitated and less than 5,000 hectares has been certified and is in a 'stable condition' (*Environmental Protection Act 1994* (Qld) (EP Act), s111A). For a stable condition to exist, rehabilitated land must be safe and structurally stable, not cause environmental harm, and be able to sustain a PMLU. Land suitability is an agricultural land evaluation method that has been used extensively throughout Queensland to decide appropriate agricultural land uses, including whether beef cattle grazing can be undertaken sustainably on land rehabilitated after open-cut coal mining.

This technical paper presents a leading practice approach for evaluating beef cattle grazing as a sustainable PMLU in the Bowen Basin region. Eleven land use limitations (soil and land attributes that impede production) affect the suitability of rehabilitated land for beef cattle grazing. These land use limitations include plant production factors (water availability, soil salinity, nutrient deficiency, and nutrient availability and toxicity), land surface factors (soil surface condition, rockiness, land slope gradient, and microrelief) and degradational factors (water erosion, sub-soil erosion risk, and depth to potentially acid forming materials). Land suitability assessment is used to evaluate these land use limitations and rank rehabilitation as suitable (Class 1, Class 2, and Class 3) or unsuitable (Class 4 and Class 5) for beef cattle grazing according to the severity of limitations.

A rehabilitated land suitability framework for beef cattle grazing in the Bowen Basin is provided. As an evaluation tool, this framework defines rehabilitation that is suitable for beef cattle grazing as a PMLU and delineates it from rehabilitation that is permanently unsuitable. The framework also defines material (i.e., soil and spoil) geochemical and landform geometry (e.g., slope) criteria that must be met for rehabilitation to be considered suitable. These criteria should be used to inform the rehabilitation planning phase to ensure rehabilitation is purposefully constructed by considering known land use limitations associated with PMLU requirements.

It is recognised that not all rehabilitated land will be suitable for beef cattle grazing. In some situations it may be desirable to graze rehabilitation areas that have been assessed as unsuitable. This may be for commercial or land stewardship reasons (e.g., grazing for natural resource management reasons) and will require careful management to prevent overgrazing and avoid land degradation. Grazing of unsuitable rehabilitation areas should be recognised lower in priority to achieving and maintaining a stable condition. If rehabilitation is deemed unsuitable (Class 4 or Class 5) it cannot sustain beef cattle grazing as a PMLU.

This is the first technical paper in a series of two. A subsequent technical paper will address property management planning aspects of transitioning artificial landforms created by open-cut coal mining into functional, viable, and sustainable landscapes for beef cattle grazing as a PMLU.

1 Introduction

Modern guidelines for agricultural land evaluation in Queensland have existed since 1990 (Queensland Government, 1990; 2015). Built on a framework developed by the Food and Agriculture Organization of the United Nations (FAO, 1976), the guidelines assist in deciding appropriate agricultural land uses. This is essential to addressing sustainability issues including land and water degradation (Queensland Government, 2015), biodiversity conservation, climate change, and food security. Whilst these broad sustainability issues are complex, land is first a biophysical resource, and agricultural land evaluation is based on the inherent characteristics or attributes of land and soil. *Land capability* and *land suitability* are the two most extensively used classification schemes. Whilst these schemes share the principle of stratified classification based on the severity of attribute limitations derived from land resource survey, outcomes are dissimilar, and the schemes are useful for different purposes.

In land capability, land uses are defined broadly, and outcomes cannot be used for detailed land use planning or management (Queensland Government, 1990). The scheme's usefulness is restricted to evaluation of a wide range of land uses at small, reconnaissance scales (i.e., 1:250,000 or smaller) (Queensland Government, 2015). In contrast, land suitability evaluates land attributes based on requirements for specific land uses. It is the preferred classification scheme where specific land use information is required at medium or large scales (i.e., 1:50,000 or larger), for example beef cattle grazing at a property-scale. For that reason, land suitability has superseded land capability and is the recommended scheme for use by the Queensland mining industry (Queensland Government, 1995).

In December 2022 there was 215,555 hectares (ha) of unrehabilitated mining disturbance in Queensland (Queensland Government, 2022). Approximately 80 % of this disturbance is attributed to coal mining (Queensland Government, 2022), predominantly in the Bowen Basin, where it often encroaches on agricultural land historically cleared of native vegetation and developed for beef cattle grazing. Consequently, most of the 49,061 ha of coal mine rehabilitation completed to date (Queensland Government, 2022) has a beef cattle grazing post-mining land use (PMLU). At the end of 2022, some 4,781 ha of coal mine rehabilitation had been progressively certified (*Environmental Protection Act 1994* (Qld) (EP Act), s318ZD) and 3,666 ha (or 75 %) of this has a beef cattle grazing PMLU (unpublished data).

Minor areas of beef cattle grazing PMLU rehabilitation have been grazed by cattle, usually as short-term 'trials' of up to a few years duration, and then discontinued. These trials have focused on various grazing productivity metrics to infer sustainable land use. These metrics include, for example, pasture growth and carrying capacity (Paton et al., 2021), cattle live weight gain (Melland et al., 2021), stocking rates and grazing pressures (Grigg et al., 2002; Grigg et al., 2007), and modelling of longer-term pasture and animal production (Grigg et al., 2007; Clewett et al., 2021). However, the usefulness of productivity-focused grazing trials in deciding land use sustainability is limited because rehabilitated land that is 'suitable' for cattle grazing may be unproductive during trials due to seasonal rainfall variability (or in the longer term, drought). Similarly, rehabilitated land that is 'unsuitable' may be productive for short periods in better seasons with above average rainfall, and during trials this may lead to erroneous conclusions about land use sustainability. This effect is highlighted by Grigg et al. (2007) who reported that variations in seasonal rainfall had an overwhelming influence on pasture production during a rehabilitation grazing trial. Therefore, when deciding if rehabilitated land can sustain a beef cattle grazing PMLU, seasonally driven production metrics (e.g., pasture growth) and decision-based production metrics (e.g., stocking rates) are likely to provide an incorrect appraisal of land use sustainability.

An alternative approach is agricultural land evaluation by FAO (1976) and Queensland Government (1990, 2013, 2015). In land suitability assessment the inherent characteristics of the soil and land are compared to land use requirements, in this case for beef cattle grazing. Given the potential for rainfall variability to obfuscate grazing trial outcomes, an approach that is independent of seasonal conditions is needed to determine sustainability. Land suitability assessment provides a reliable means of determining the sustainability of a beef cattle grazing PMLU in rehabilitation areas regardless of seasonal conditions and grazing history.

This is the first in a series of technical papers focused on beef cattle grazing PMLU rehabilitation in the Bowen Basin. The intent of these papers it to provide clear, practical, straightforward advice for rehabilitation practitioners, government regulators, rehabilitation graziers, and other stakeholders. The two papers are:

- Technical paper 1 – Rehabilitated mined land suitability for beef cattle grazing in the Bowen

Basin
- Technical paper 2 – Property development planning for grazing on rehabilitated mined land in the Bowen Basin..

2 Queensland's land suitability scheme

2.1 Suitability classes

Queensland Government (2015) explains the land suitability scheme. It states that in Queensland, there are five land suitability classes for each specific agricultural land use (Queensland Government, 2015) (Table 1). These classes are said to define land in terms of suitability for a particular use which allows optimum, sustainable production with current technology, while minimising degradation to the land. Land is less suitable for a use such as beef cattle grazing as the severity of limitations increase, reflecting:

- Reduced potential for production and/or
- Increased inputs required to achieve an acceptable level of production and/or
- Increased inputs required to prepare the land for successful production and/or
- Isncreased inputs required to prevent land degradation.

In this stratified classification, the Class 3/Class 4 boundary is the most important threshold, because it separates land that is suitable for a specific land use from land that is not (Queensland Government, 2015).

Table 1. Land suitability classes for agricultural land evaluation in Queensland (Queensland Government, 2015)

Class	Classification	Limitations	Description
1	Suitable	Negligible	Highly productive land requiring only simple management practices to maintain economic production.
2	Suitable	Minor	Land with limitations that either constrain production or require more than the simple management practices of class 1 land to maintain economic production.
3	Suitable	Moderate	Land with limitations that either further constrain production or require more than those management practices of class 2 land to maintain economic production.
4	Unsuitable	Severe	Currently unsuitable land. The limitations are so severe that the sustainable use of the land in the proposed manner is precluded. In some circumstances, the limitations may be surmountable with changes to knowledge, economics, or technology.
5	Unsuitable	Extreme	Land with extreme limitations that preclude any possibility of successful sustained use of the land in the proposed manner.

Classes 1, 2, and 3 are considered suitable for a specified agricultural land use because the benefits from using the land (for that particular use) outweigh the inputs required to initiate and maintain production. Class 4 and 5 are unsuitable without further investigation and/or major changes in economics, technologies, or management expertise. Many Class 5 lands have physical characteristics that totally preclude any form of agricultural development (e.g., slope gradients) and land that falls into this category will likely always be unsuitable for agricultural use.

2.1.1 Beef cattle grazing systems

Contemporary grazing systems in the Bowen Basin aim to produce young, finished, grassfed, export quality cattle without inputs other than pasture development. Most production is based around exotic grass-legume pastures, sometimes referred to as "improved pastures". Improved pasture development in many areas is dominated by *Cenchrus ciliaris* (Buffel grass), though other species have roles in certain circumstances. Considering descriptions in Queensland Government (2015) and

Shields and Williams (1991), typical grazing systems in the Bowen Basin can be paired to suitability classes (Table 2).

Table 2. Grazing systems and suitability classes for beef cattle grazing in the Bowen Basin

Suitability class		Grazing system	Description
1	Suitable	Fattening / finishing	Land capable of attaining maximum grazing productivity, i.e. production of young, finished, grass fed, export quality cattle in most seasons.
2	Suitable	Growing	Land on which younger cattle perform well but may be difficult to finish at a young age, depending on seasonal conditions.
3	Suitable	Breeding	Land able to carry breeding stock all year round depending on seasons.
4	Unsuitable	Sometimes	Land that is unsuitable most of the time but may be grazed in better seasons for short periods in conjunction with other country (see Section 4).
5	Unsuitable	Never	Land that is not suitable for cattle grazing.

2.1.2 Pasture requirements

Most beef cattle grazing PMLU rehabilitation features Anthroposols (Isbell and NCST, 2021) (i.e., human-made soils), which are constructed by placing a thin veneer of pre-existing topsoil over mine spoils. These new soil profiles typically have an A horizon (200 mm average depth) of preserved topsoil over a B horizon (to 900 mm assumed depth) of preferably Permian-aged mine spoil (BHP Coal, 2017), but often Tertiary-aged, and sometimes Quaternary-aged spoil. Mine spoils of similar geological age have broadly common inherent characteristics that profoundly affect rehabilitation outcomes, in particular chemical and physical properties that lead to erosion (So et al., 1998) and biophysical characteristics that affect the viability of PMLUs such as cattle grazing (Maczkowiack et al., 2013).

Like unmined land developed for grazing, beef cattle grazing PMLU rehabilitation should be dominated by desirable pasture species, which are suitable for modern grazing systems. A good grazing pasture in beef cattle grazing PMLU rehabilitation will contain a diversity of dense and healthy plants, which are dominated by desirable species (i.e., 3P species). It will also comprise legumes, forbs, and other seasonal native species, appropriate for the soil and land conditions.

Desirable, 3P species are:

- Perennial: long lived, present all year round and, with extensive root systems that can effectively extract water and nutrients from the soil profile, and are resilient to seasonal conditions and grazing.
- Productive: produce a large amount of forage over time, with sufficient nutrition for livestock production.
- Palatable: high proportion of leaf which is actively selected by cattle.

Most existing beef cattle grazing PMLU rehabilitation is dominated by exotic 3P grasses Buffel grass and *Chloris gayana* (Rhodes grass), and in some instances monocultures of each have established. Other introduced grasses that have been observed doing well include *Bothriochloa* spp. (Indian and Creeping bluegrasses), *Setaria incrassata* (Purple Pigeon grass), and *Panicum* ssp. (Panics). Useful native 3P grasses include *Heteropogon contortus* (Black Speargrass), *Bothriochloa bladhii* (Forest bluegrass), *Dichanthium sericeum* (Queensland bluegrass), and *Capillipedium parviflorum* (Scented top). Legume establishment and species vary considerably in rehabilitation depending on soil characteristics and microclimates. Common legumes that persist are *Stylosanthes* spp. (Townsville and Seca Stylos), *Desmanthus* spp. (Desmanthus), *Chamaecrista rotundifolia* (Wynn Cassia), *Clitoria ternatea* (Butterfly Pea), *Macroptilium bracteatum* (Burgundy Bean), and *Macroptilium atropurpureum* (Siratro).

For beef cattle grazing PMLU rehabilitation, the inherent characteristics of new soil profiles and landforms will determine the quality, productivity, and sustainability of sown pastures, and its suitability for beef cattle grazing land use.

2.2 Suitability framework

Since the 1960s, many government-led land suitability assessments have been completed across Queensland. Drawing on this library of work, Queensland Government (2013) sets out land suitability frameworks for each regional cropping area, including “Central Queensland Inland Fitzroy and Southern Burdekin region” that overlies the Bowen Basin. Unlike frameworks for several regions that prescribe land use requirements for beef cattle grazing and other land uses in addition to cropping, the framework relevant to the Bowen Basin does not.

2.2.1 Land use requirements, limitations, and limitation categories

There are certain land use requirements for beef cattle grazing. A list of land use requirements for crop and pasture growth, machinery use, land preparation, irrigation, and the prevention of land degradation has been defined for agricultural land uses in Queensland (Queensland Government, 1990; 2015). Limitations are soil or land characteristics that impede agricultural production. These limitations are determined from soil and land diagnostic attributes and are usually expressed as land use requirements that are stated in the negative. Some limitations have universal application in land suitability frameworks (e.g., soil water availability) (Queensland Government, 2015). This is not surprising given soil water availability is typically the most limiting factor in dryland cropping systems (Queensland Government, 2015) and it similarly constrains total dry matter yield of pastures (Shields and Williams, 1991).

In this report, the land use requirements and limitations important to cattle grazing on land rehabilitated after coal mining, and the relevant soil and land attributes, have been identified through literature review. Reviewed literature included government agricultural land evaluation guidelines and regional suitability frameworks for Queensland (Queensland Government, 2013; 2015), regionally relevant government-led land suitability assessments (Shields and Williams, 1991; Burgess, 2003), industry-led mined land rehabilitation research (So et al. 1998, Carroll et al. 2001, Grigg et al. 2002; Grigg et al. 2007), relevant tropical pasture production studies and other research, plus a thorough local knowledge of coal mine rehabilitation practices and outcomes.

Eight land use requirements and eleven limitations were identified as important for beef cattle grazing PMLU rehabilitation (Table 3). This list is generally consistent with earlier government-led suitability frameworks for pasture development and cattle grazing in central Queensland (Shields and Williams 1991 and Burgess, 2003). Limitations can be grouped into three categories, depending on their effect:

- Plant production factors: water availability (M), salinity (S), nutrient deficiency (Nd) and nutrient availability and toxicity (Nr).
- Land surface factors: soil surface condition (P), rockiness (R), land slope gradient (Ts) and surface microrelief (Tm).
- Degradational factors: water erosion (Ea), sub-soil erosion risk (Eb), and depth to potentially acid forming materials (D).

Table 3. Land use requirements, limitations, and soil and land attributes used to assess each limitation for beef cattle grazing PMLU rehabilitation

Land use requirements	Limitation (code)	Assessment attributes or indicators
Adequate water supply	Water availability (M)	Soil water storage.
Adequate soil nutrition	Nutrient deficiency (Nd)	Available phosphorus (P) in surface soil (0.1 m depth).
	Nutrient availability and toxicity (Nr)	Acidity/alkalinity as $pH_{1:5\ WATER}$ in surface soil (0.1 m depth).
Seedbed suitable for pasture establishment	Surface condition (P)	Soil surface condition (by observation).
Effective rooting depth (ERD)	Salinity (S)	Salinity as ECe (dS/m) in ERD.
Rock free	Rockiness (R)	Size (cm) and abundance (%) of coarse fragments.
Topography	Slope (Ts)	Landform element slope (%).
	Microrelief (Tm)	Amplitude (depth, m) of furrows caused by deep ripping.
Sustainable rates of soil loss by erosion	Water erosion (Ea)	Landform element slope (%) and surface soil sodicity.
	Subsoil erosion (Eb)	Sodicity in subsoil (0.5 m depth).
Free of acid and metalliferous drainage (AMD)	Potentially acid forming materials (D)	Depth (m) to potential or actual strongly acid conditions (pH <4.5).

The listed land use requirements and limitations are relevant to beef cattle grazing PMLU rehabilitation in the Bowen Basin region. Application to suitability assessment of rehabilitated land in different regions may be useful, but this should be undertaken with caution and the list should be modified as necessary to suit regional conditions.

2.2.1.1 Water availability (M)

The amount of water that can be stored (i.e., stored rainfall), in the new soil profile and later accessed by plant roots will restrict the growth of sown pastures in beef cattle grazing PMLU rehabilitation (Grigg et al., 2001). This is essentially controlled by soil depth, soil texture, and the presence of physicochemical root barriers.

Consistent with earlier regional assessments (Shields and Williams, 1991) the ERD of pasture species, which is the depth to which pasture roots can grow and function effectively, is assumed to be 0.6 m in rehabilitation. Where ERD is reduced by physical impediments i.e., compacted layers or rock, or chemical impediments i.e., subsoil pH <5.5, ECe >8 dS/m or exchangeable sodium percentage (ESP) >20 %, this will cause a corresponding reduction in plant available water capacity (PAWC) and therefore limitation subclass.

So et al. (1998) determined PAWC for 14 mine spoils and 12 soils from 12 Bowen Basin coal mines. Pairing results for soils and spoils for each mine, typically clayey Anthroposols (20 cm topsoil overlying 40 cm of mine spoil) had PAWC values ranging from 34 to 114 mm (mean = 67 mm, standard deviation, SD = 23). However, soils and mine spoils, including those with relatively high PAWC values, were variably salt affected, being either highly saline and/or strongly sodic. On this basis, most new soil profiles are likely to have a water availability limitation i.e., M2-M5, due to a chemical impediment that restricts rooting depth, with the severity of the limitation increasing as rooting depth and PAWC decrease.

Typically, clayey Anthroposols with an ERD ≥60 cm are considered to have a negligible water availability limitation (M1) for pasture production in beef cattle grazing PMLU rehabilitation (Table 4). Benchmark values used to differentiate subclass limitations are aligned with those used in previous land suitability assessments for relevant sown pastures in Queensland (McClurg, 1999).

Table 4. Criteria used to differentiate subclass limitations for water availability (M)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
PAWC (mm)	>75	75-60	<60-40	<40-30	<30

2.2.1.2 Nutrient deficiency (Nd)

Soil nutrient deficiency is a major limiting factor to pasture and cattle production in central Queensland (Shields and Williams, 1991) and northern Australia more generally (Dixon et al., 2020). Nitrogen (N) and P are the dominant nutrients controlling grazing productivity (Jones, 1990) and combined levels of Total-N and Available-P have been used to evaluate overall soil nutrition in historical land suitability assessments (Burgess, 2003).

It is well known that the productivity of sown pastures in northern Australia generally declines over time due to reduced N availability (Meyers and Robbins 1991). Most of these pastures were sown without legumes due to lack of suitable pasture legume varieties (Peck et al., 2012). This is likely why previous land suitability assessments assumed long term N availability depends solely on the amount of soil organic-N and its rate of mineralisation into forms available to plants, and hence assessed Total-N. This is no longer the case and there are now commercially available persistent legumes for a variety of land types throughout Queensland (Peck et al., 2012) including species observed doing well on rehabilitated lands in the Bowen Basin (Grigg et al., 2000). Some legume varieties may have the capacity to meet grazed pasture N requirements (Thomas 1995). For this reason, Total-N is not considered an indicator of nutrient deficiency here.

Available-P, or bicarbonate extractable-P, remains an important surrogate for general soil fertility. In grazing pastures, P is typically the most limiting nutrient for legumes (Jones, 1990) and, where legumes and grasses are competing for limited soil nutrients, it may be required in significant quantities for legume establishment (Cech et al., 2010). For commonly sown Buffel grass, maximum production is achieved at a critical Available-P level of about 20 mg/kg (Campbell et al., 2012), indicating a negligible (Nd1) limitation to pasture production in rehabilitation. More generally, Dixon et al. (2020) categorized northern Australian soils based on Available-P ranging from adequate (>8 mg/kg) to acutely deficient (<4 mg/kg) for cattle grazing land use. These benchmark values were used to differentiate subclass limitations here (Table 5). The critical Nd3/Nd4 threshold value is aligned with that used in other contemporary land suitability assessment for relevant sown pastures in central Queensland (McClurg, 1999).

Table 5. Criteria used to differentiate subclass limitations for nutrient deficiency (Nd)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Available-P (mg/kg) in 0-0.1 m soil depth increment	>20	20-14	<14-8	<8-4	<4

2.2.1.3 Nutrient availability and toxicity (Nr)

In the Bowen Basin, soil pH can vary from 4.0 to 8.8 in natural profiles (Shields and Williams, 1991; Burgess, 2003). However, Anthroposols in rehabilitation may have a wider pH range if affected by acid producing mineral wastes or very strongly alkaline overburdens. A soil pH between 6.0 and 7.5 has a negligible limitation to the growth of most plants (Hall, 2008) and between 6.6 and 7.3 is considered neutral (Hazelton and Murphy, 2007). The critical Nr3/Nr4 boundary corresponds with an acid soil pH of 5.6, below which aluminum solubility increases and its toxicity and effects on P availability will impact plant growth, and an alkaline soil pH of 8.4, above which P availability is also reduced (Hall, 2008) (Table 6).

Table 6. Criteria used to differentiate subclass limitations for nutrient availability and toxicity (Nr)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
pH in 0-0.1 m soil depth increment	7.3-6.6	<6.6-6.0 >7.3-7.9	<6.0-5.6 >7.9-8.4	<5.6-5.0 >8.4-9.0	<5.0 >9.0

2.2.1.4 Surface condition (P)

This limitation is primarily concerned with restrictions to emergence of seedlings and establishment of pasture species in rehabilitation due to soil surface conditions. In general, as the soil surface becomes coarser or crusted and hard-set, tropical pasture seedling emergence and establishment is reduced (French and Clarke, 1993). This can be exacerbated in rehabilitation if topsoil is not used and/or is mixed with sodic mine spoils that form surface seals which reduce infiltration and moisture available for germination (Harwood et al., 1999). The proposed subclass boundaries for this limitation are generally consistent with previous studies in unmined lands (McClurg; 1999) (Table 7).

Table 7. Criteria used to differentiate subclass limitations for surface condition (P)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Surface condition	Fine (peds <10mm)	Coarse (peds >10mm)	Surface crust	Very hard setting	Massive

2.2.1.5 Salinity (S)

Salinity refers to elevated levels of soluble salts within the ERD (0-0.6 m depth). Primary salinity is a particular limitation to pasture establishment, production, and resilience in mine rehabilitation (Harwood et al., 1999), as most overburdens available for rehabilitation are inherently saline to highly saline (Grigg et al., 2000; Grigg et al., 2001). Tertiary aged spoils are typically the most saline, and relatively more saline than Permian aged spoils and available topsoils (Grigg et al., 2000), though these materials may still be salt affected. Bell et al., (1991) reported Tertiary aged spoils were highly saline (mean ECe = 9.8 dS/m, SD = 7.7, n = 25) while So et al., (1998) reported similar results for spoils of mixed geological ages across the Bowen Basin (mean ECe = 10.31 dS/m, SD = 8.1, n = 14).

The salinity of spoil placed at or near the surface of rehabilitation is important because the tolerance of tropical pasture species to saline soil conditions is variable. Soil salinity thresholds for commonly sown grasses Buffel and Rhodes grasses are 5.5 and 7.0 dS/m, respectively, with the yield of Buffel grass reduced by half at 10.4 dS/m (Russell, 1976). Tropical legumes are generally less salt tolerant than grasses. For widely sown legumes Stylo and Siratro threshold ECe values are 2.4 and 2.0 dS/m, respectively (Russell, 1976). Because mine spoils and derived Anthroposols are generally salt affected, soil salinity thresholds at which key tropical grass and legume species yields are affected have been used to determine limitation subclasses.

Anthroposols with salinity (ECe) <2 dS/m in the ERD are considered to have a negligible salinity limitation (S1) for pasture production (Table 8). Due to the dominance and importance of Buffel grass in rehabilitation, and throughout the Bowen Basin and northern Australia more generally, the salinity level at which a 50 % yield reduction occurs is used to differentiate suitable and unsuitable rehabilitation (S3/S4 boundary). Other subclass boundaries are generally in accordance with common salinity ratings (e.g., those in Hazelton and Murphy, 2007).

Table 8. Criteria used to differentiate subclass limitations for salinity (S)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
ECe (dS/m) in ERD (0-0.6 m depth increment)	<2	2-4	>4-10	>10-16	>16

2.2.1.6 Rockiness

Coarse rock fragments in Anthroposols can interfere with machinery used in rehabilitation and impede access and trafficability. Dense rock surface coverages can also act as a mulch and prevent seedling emergence and establishment. Assessment here is based on the size and abundance of coarse fragments on the new soil surface i.e., presence of gravel, cobble, stone, and boulders on the soil surface (Table 9). Nil coarse fragments present a negligible limitation (R1) for pasture production in rehabilitation. Benchmark values used to differentiate subclass limitations correspond to increasing surface rockiness.

Table 9. Criteria used to differentiate subclass limitations for rockiness (R)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Gravel, 20 – 60 mm (%)	<20	20-50	>50-70	>70-85	>85
Cobble, 60 – 200 mm (%)	<10	10-20	>20-50	>50-75	>75
Stone, 200 – 600 mm (%)	<2	2-10	>10-20	>20-50	>50
Boulders, >600 mm (%)	0	<2	2-10	>10-20	>20

2.2.1.7 Topography, slope gradient (Ts) and microrelief (Tm)

The topography limitation considers the overall slope and surface unevenness of rehabilitation. These factors affect access and safe operation of agricultural machinery and equipment, the ability to efficiently move stock across the land, and pasture production.

Historically, a range of slope gradients have been considered unsafe for general agricultural machinery use and therefore regarded as unsuitable, for example >25 % (Queensland Government, 2015) and >20 % (Queensland Government, 1990). Specifically for improved pastures in central Queensland, McClurg (1999) considered slope gradients >15 % unsafe and unsuitable. On rehabilitated land, the impact of slope gradient on the safe cross-gradient operation of agricultural machinery is worsened by a microrelief of steeply incised furrows due to deep ripping. For this reason, slope gradients >15 % on rehabilitated land are considered unsafe and unsuitable for machinery operation and this threshold limit is used to define the critical Ts3/Ts4 boundary (Table 10).

Table 10. Criteria used to differentiate subclass limitations for slope gradient (Ts)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Slope gradient (%)	<5	5-10	<10-15	>15-20	>20

Unlike conventional land evaluation that considers microrelief mainly in the context of gilgai, in rehabilitation the effects of furrows created by the deep ripping of new soil profiles with large bulldozers is considered. Observation suggests that these furrows are long-lived (>25 years) unless some form of land levelling or smoothing is conducted to reduce amplitude. Where deep furrows persist in rehabilitation, the furrow-mound-furrow surface can lead to linear patchiness in vegetation with pasture persisting on mounds and not in furrows. This is somewhat unexpected, because micro-depressions in unmined grazing landscapes can encourage high amounts of biomass due to increased soil moisture and other factors (Rietkerk et al., 2000).

One explanation for this phenomenon in rehabilitation is differing soil conditions in mounds and furrows due to the mixing of topsoil with underlying mine spoil during deep ripping. The implications of this intra-rehabilitation soil heterogeneity on pasture establishment and persistence under grazing are not well understood. Undoubtedly, soil development in bare furrows will be retarded in the absence of positive plant-soil feedbacks, including organic matter build-up and nutrient cycling. This means that furrows may remain bare indefinitely and, as these bare furrows occupy a considerable proportion of the soil surface in rehabilitation, this will reduce the total pasture biomass produced and the amount of feed available for grazing.

It is common practice to deep rip all rehabilitation to relieve compaction, improve infiltration and reduce runoff (Grigg et al., 2000). Most rehabilitation is likely to have a microrelief limitation (Tm2-Tm5) due to the existence of ripping furrows, with the severity of the limitation increasing as the amplitude of furrows increases. On unmined land, gilgai vertical intervals >0.3 m impede cultivation and trafficability, with the severity of the limitation increasing with amplitude and the proportion of land affected (McClurg, 1999). On rehabilitated land, the entire area of rehabilitation will nearly always be affected by deep ripping and the critical Tm3/Tm4 threshold value that separates suitable and unsuitable land is set at 0.4 m depth (Table 11). The Class 3 criterion is 0.2-0.4 m and this encompasses the Class 3 / Class 4 threshold value of 0.3 m used in historical assessments (e.g., Shields and Williams 1991).

Table 11. Criteria used to differentiate subclass limitations for micro-relief (Tm)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Micro-relief, vertical (m)	0	<0.2	0.2-0.4	>0.4-0.6	>0.6

2.2.1.8 Water erosion (Ea)

Water erosion is a significant risk to achieving a stable condition in rehabilitation. Measured rates of sediment loss from coal mine rehabilitation exceed those from other land uses in the region (Carroll et al., 2010). Various studies have demonstrated the long-term key to reducing erosion in rehabilitation is a high percentage of vegetative groundcover (So et al., 1998; Loch, 2000; Carroll and Tucker, 2000; Carroll et al., 2000). However, in the short-term, prior to vegetation establishment, rehabilitation is vulnerable to erosion (Loch, 2000; Carroll et al., 2000) and the amount of sediment loss from slopes is affected by spoil properties and slope geometries (Grigg et al., 2001; So et al., 1998).

Field experimentation has shown erosion rates typically exceed 70t/ha/y when there is insufficient vegetative groundcover (Carroll et al., 2000). The rate of erosion and the length of time needed for sufficient groundcover to establish to control erosion are both greater on steeper slopes (Carroll et al., 2000). Sometimes vegetation may not establish at all and where highly dispersive materials are present, tunnel and gully erosion may lead to landform failure (Vacher et al., 2004).

Available topsoils can be sandy, non-cohesive and prone to detachment-driven erosion (So et al., 1998) or clayey, sodic, and prone to dispersion-led erosion. A high proportion of Queensland soils are affected by sodicity (Raine and Loch, 2003), and subsoil sodicity is widespread in the local region (Irvine and Doughton, 2001). During topsoil stripping, topsoil may be contaminated with sodic soil horizons, resulting in soil dispersion and erosion losses. In addition, post-mining landforms in the Bowen Basin typically have steep outer slopes of between 10 % gradient (5.74° angle) and 30 % gradient (17° angle). For these reasons, most rehabilitation is likely to have a water erosion limitation (Ea2-Ea5), with the severity of the limitation increasing with slope gradient and sodicity (ESP) (Table 12).

Table 12. Criteria used to differentiate subclass limitations for water erosion (Ea)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Slope (%), ESP <6 (%) in 0-0.1 m soil depth increment	<5	5-8	>8-12	>12-18	>18
Slope (%), ESP 6-14 (%) in 0-0.1 m soil depth increment	<3	3-6	>6-10	>10-12	>12
Slope (%), ESP >14 (%) in 0-0.1 m soil depth increment	<1	1-2	>2-4	>4-6	>6

2.2.1.9 Subsoil erosion risk (Eb)

The potential for subsoil dispersion and erosion is a major risk for coal mine rehabilitation because most spoils are sodic to very strongly sodic. So et al. (1998) reported spoils of mixed geological ages were very strongly sodic (mean ESP = 22.5 %, SD = 13.3, n = 14). In a study focused on Tertiary-aged spoils, Henderson et al. (2004) reported similar values (mean ESP = 23.6 %, SD = 18.2, n = 40). The combined data sets from these two earlier studies present variable ESP values for spoils across the Bowen Basin (mean ESP = 23.4 %, SD = 17.2, n = 54).

It is likely that most rehabilitation will have a subsoil erosion risk limitation (Eb2-Eb5), and the severity of this limitation will increase as the ESP increases (Table 13). Here, ESP = 23 % at 0.5 m depth is adopted as the critical Eb3/Eb4 threshold value to differentiate suitable and unsuitable beef cattle grazing PMLU rehabilitation.

Table 13. Criteria used to differentiate subclass limitations for subsoil erosion risk (Eb)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
ESP (%) at 0.5 m depth	<6	6-14	>14-23	>23-34	>34

2.2.1.10 Potentially acid forming materials (D)

Potentially acid forming (PAF) materials are sulphide-bearing mine spoils and mineral wastes from coal processing. When exposed to oxygen and water, sulphides oxidize to produce acid and metalliferous drainage (AMD). AMD is typically characterised by low pH and elevated dissolved metals, though the composition of drainage can vary substantially (Australian Government, 2016). AMD occurs sporadically throughout Bowen Basin mines, and despite it being one of the most serious and potentially enduring environmental problems for the mining industry globally (INAP, 2014), its potential impacts on PMLUs and mine closure are not well understood locally. Where the root zone is potentially affected by AMD, the rehabilitated land is considered unsuitable for cattle grazing. Controlled placement and burial of PAF materials will be important, and a trigger value of pH=4.5 is adopted here as the critical D3/D4 threshold immediately beneath the root zone (Table 14). This pH threshold flags an extremely acid condition (Baker and Eldershaw, 1993) that is likely due to oxidation of sulphides (e.g., pyrite and other forms). If near root zone acidity flags the presence of PAF materials in the rehabilitation area, then a geochemical testing program, for example AMIRA (2002), should be performed. Such a program will determine the current and potential long-term geochemical characteristics of the waste materials to inform an appropriate strategy to prevent or mitigate the impacts of AMD.

Table 14. Criteria used to differentiate subclass limitations for potentially acid forming materials (D)

Indicator	Suitable			Unsuitable	
	Class 1	Class 2	Class 3	Class 4	Class 5
Strongly acid conditions (pH <4.5) within (x) m depth	>3	3-2	<2-0.9	<0.9-0.6	<0.6

2.2.2 Land suitability framework for beef cattle grazing PMLU rehabilitation

The following land suitability framework for beef cattle grazing PMLU rehabilitation is a matrix for each limitation discussed above, showing the suitability subclass for each limitation (Table 15). The framework is sometimes referred to as the suitability 'rule set' for beef cattle grazing in rehabilitation. The overriding objective in application of the framework is to decide a suitability class for a rehabilitation area. All suitability subclasses should be considered. The overall suitability class for a rehabilitation area is determined by its most severe suitability subclass.

3 Delivering suitable rehabilitation

For beef cattle grazing PMLU rehabilitation, human-made Anthroposols and artificial landforms will need to have land use limitation subclasses appropriate to cattle grazing land use requirements, as defined in the regional framework in this leading practice technical paper (see Table 15). In parallel with progressive rehabilitation and closure (PRC) plan schedules (EP Act, s126D) that lay out rehabilitation milestones and when each milestone is to be achieved, this leading practice paper sets the quality standard that suitable beef cattle grazing PMLU rehabilitation will need to achieve. This will require diligent planning, execution, and evaluation.

3.1 Planning

It is fundamental to delivering beef cattle grazing PMLU rehabilitation that the suitability framework (see Table 15) is used as a guide to rehabilitation requirements in the planning phase, before landforms and soils are constructed.

Table 15. Regional land suitability framework for beef cattle grazing PMLU rehabilitation in the Bowen Basin

Limitation	Indicator	Suitable			Unsuitable	
		Class 1	Class 2	Class 3	Class 4	Class 5
Water availability (M)	Soil water storage (mm)	>75	75-60	<60-40	<40-30	<30
Nutrient deficiency (Nd)	Available-P (mg/kg) in 0-0.1 m depth increment	>20	20-14	<14-8	<8-4	<4
Nutrient availability and toxicity (Nr)	pH in 0-0.1 m depth increment	7.3-6.6	<6.6-6.0 >7.3-7.9	<6.0-5.6 >7.9-8.4	<5.6-5.0 >8.4-9.0	<5.0 >9.0
Surface condition (P)	Surface condition	Fine (peds <10mm)	Coarse (peds >10mm)	Surface crust	Very hard setting	Massive
Salinity (S)	ECe (dS/m) in ERD (0-0.6 m depth increment)	<2	2-4	>4-10	>10-16	>16
Rockiness (R)	Gravel, 20 – 60 mm (%) Cobble, 60 – 200 mm (%) Stone, 200 – 600 mm (%) Boulders, >600 mm (%)	<20 <10 <2 0	20-50 10-20 2-10 <2	>50-70 >20-50 >10-20 2-10	>70-85 >50-75 >20-50 >10-20	>85 >75 >50 >20
Slope (Ts)	Slope grade (%)	<5	5-10	<10-15	>15-20	>20
Microrelief (Tm)	Vertical interval (m)	0	<0.2	0.2-0.4	>0.4-0.6	>0.6
Water erosion (Ea)	Slope (%), ESP <6 (%) in 0-0.1 m soil depth increment Slope (%), ESP >6-14 (%) in 0-0.1 m soil depth increment Slope (%), ESP >14 (%) in 0-0.1 m soil depth increment	<5 <3 <1	5-8 3-6 1-2	>8-12 >6-10 >2-4	>12-18 >10-12 >4-6	>18 >12 >6
Subsoil erosion (Eb)	ESP (%) at 0.5 m depth	<6	6-14	>14-23	>23-34	>34
PAF materials (D)	Strongly acid conditions (pH <4.5) within (x) m depth	>3	3-2	<2-0.9	<0.9-0.6	<0.6

3.1.1 Material suitability

Available materials (spoils and soils) must be characterised before use to ensure:

- Materials with favourable geochemical properties are selected for use, and/or
- Ameliorants and fertiliser requirements can be specified, and/or
- Unsuitable materials are not used.

Unsuitable materials are those with severe and extreme limitations for beef cattle grazing land use.

3.1.1.1 Subsoil suitability

For Anthroposols in beef cattle grazing PMLU rehabilitation, subsoils (0.2 – 0.9 m depth) will typically be spoils, though other materials may be present (e.g. coal mineral wastes). Subsoil provides mechanical anchorage for plants and contributes to soil nutrition. However, the principal role of subsoil is to store soil moisture for later plant use i.e., PAWC. Understanding subsoil limitations that restrict root proliferation and access to stored water is therefore important in delivering suitable beef cattle grazing PMLU rehabilitation.

Excess salt (salinity and sodicity) is a common limitation in subsoils that restricts rooting depth and root proliferation and increases dispersion and erosion risk. Salinity and sodicity are interrelated (Hall, 2008). Although higher salt levels may improve the structural stability of sodic spoils, the salinity levels needed will impact adversely on pasture establishment and production. Spoil materials with ECe ≤10 dS/m and ESP ≤23 % are suitable for use as subsoil (Table 16 and Table 17) however, many overburdens will exceed one or both thresholds.

Gypsum (calcium sulphate) is often added to sodic spoils in the Bowen Basin to improve structural stability when wet. Application rates are based on ESP values and typically range from 5 to 20 t/ha, sometimes higher. Gypsum must first dissolve into soil solution (increasing soil salinity in the short-term) for calcium to exchange with sodium on cation exchange surfaces. Spoils with ESP >23 % should not be placed at or near the surface of rehabilitation because this is the point at which amelioration or other management options are not feasible and subsoil erosion cannot be managed to ensure a stable condition is achieved.

Whilst gypsum may be used to combat sodicity, at least to some extent, nothing can be added to ameliorate salinity. Selected subsoil materials must also be 'barren' or not acid forming (NAF) in terms of AMD classification. For these reasons, subsoil materials must be carefully characterised and selected for use in rehabilitation.

Table 16. Critical salinity ranges for subsoils (0.2–0.9 m depth)

Rating	ECe (dS/m)	Suitability for use
Non-saline	<2	Suitable
Slightly saline	2-4	Suitable
Moderately saline	>4-10	Suitable, less preferred
Highly saline	>10-16	Not suitable
Extremely saline	>16	Not suitable

Table 17. Critical sodicity ranges for subsoils (0.2-0.9 m depth)

Rating	ESP (%)	Suitability for use
Non-sodic to sodic	≤14	Suitable
Strongly sodic	>14-23	Suitable, with amelioration (gypsum)
Extremely sodic	>23	Not suitable

3.1.1.2 Topsoil suitability

For most Anthroposols in beef cattle grazing PMLU rehabilitation, new surface soil (0-0.2 m depth) will be respread topsoil. Surface soils are the seedbed for germination, and the layer in which most plant nutrients and organic matter are contained and cycled. Understanding plant growth limitations within this layer, and correcting these, is essential to achieving suitable beef cattle grazing PMLU rehabilitation (Table 18).

Macro-nutrient deficiencies, particularly P, are common in natural topsoils throughout central Queensland. However, where topsoil is used in rehabilitation, micro-nutrient deficiencies will be less likely to occur. In circumstances where no topsoil is used, and pasture is required to establish directly on waste rock, overburden, or mineral wastes, then significant fertiliser applications will be needed to overcome nutrient deficiencies.

Most surface soil fertility issues can be corrected with fertiliser applications unless the material is affected by an excess of salt. Therefore, the electrical conductivity of soil solution and the percentage of sodium cations on clay exchange surfaces (i.e., ESP) are the primary parameters for deciding the suitability of surface soils for use in rehabilitation. Generally, surface soils with ECe ≤10 dS/m are suitable, though lower salinities are preferred. So et al. (1998) reported ECe >10 dS/m for many Bowen Basin mine overburdens and these materials are unsuitable for use as surface soils because they are hostile to plants. Surface soils should also have a low sodicity, and non-sodic soils with ESP ≤6 % (Hazelton and Murphy, 2007; Baker and Eldershaw, 1993) are preferred for use.

Table 18. Critical geochemical ranges for surface soils (0-0.2 m depth)

Parameter	Units	Suitable range
pH	None	5.6-8.4
Available-P	mg/kg	≥8
ECe	dS/m	≤10
ESP	%	Depends on slope gradient, see Table 15

3.1.2 Landform design parameters

For beef cattle grazing PMLU rehabilitation, final landforms will need to be designed with maximum slope gradients as follows.

- 15 % for the safe operation of agricultural machinery and equipment.
- 12 % for effective erosion hazard control.

More than 20 years ago, industry-led rehabilitation research concluded that high levels of groundcover were themselves insufficient for effective erosion hazard control in pasture-based coal mine rehabilitation and suggested slope gradients of 12 % or less would be needed (Grigg et al., 2001). This is consistent with a current industry landform design guideline that states slope gradients for Tertiary and weathered Permian aged spoils should not exceed 5 %, and for fresh Permian spoil should be no greater than between 10 % and 15 % (BHP Coal 2017). Suitable slope gradients are also a function of surface soil sodicity (see Table 15).

3.2 Evaluation

Whether beef cattle grazing PMLU rehabilitation can sustain that land use should be decided by application of the regional land suitability framework presented in this technical paper (see Table 15). The broad methodologies for agricultural land evaluation in Queensland are detailed in Queensland Government (2015). More detail can be found in the following texts:

- Surveying soil and land resources (Mckenzie et al., 2008), commonly referred to as the ‘blue book’
- Soil and land survey field handbook (NCST, 2009), commonly referred to as the ‘yellow book’
- Australian soil classification (Isbell and NCST, 2021).

To ensure an evaluation will withstand the highest level of scrutiny, it should be conducted by persons with proven competencies in land and soil resource assessment.

3.2.1 Resource assessment and mapping

A detailed field survey will be required. This should be completed at an investigation site intensity to allow final mapping at a cartographic scale or 1:25,000 or larger (i.e., 1:10,000 scale) (Table 19). Unique mapping units (UMAs) should be delineated based on soil and land attributes. In the first instance this should be soil type and landform element (i.e., slope), and the year that rehabilitation areas were completed (or rehabilitation age) will form a useful initial guide. The large cartographic scales stipulated here are appropriate because UMAs will seldom be larger than 100 ha, and each must be accurately represented and evaluated.

The number and types of investigation sites (i.e., exclusion, detailed, and analysis sites) should follow recommendations in the 'blue book' (Mckenzie et al., 2008). All fieldwork should be compliant with the 'yellow book' (NCST, 2009). Ultimately, the number and location of investigation sites, and the quality of the fieldwork, will rely on the experience, skill, and judgement of the persons involved.

Table 19. Investigation site intensity and cartographic scale (from Mckenzie et al. 2008)

Intensity	Site intensity	Publication scale
Very high, intensive	>4 sites/ha	1:2,500
High, intensive	≥1 site/4 ha	1:10,000
Moderate, detailed	≥1 site/25 ha	1:25,000

3.2.2 Land suitability assessment

The land suitability framework presented provides a basis to assess the inherent limitations of rehabilitated land and decide if it is suitable for a beef cattle grazing PMLU (see Table 15). It also provides indicators and criteria to determine the suitability of available materials, inform mine planning and landform design parameters, and guide remediation techniques. The methodology for land suitability assessment is detailed in Queensland Government (2015).

3.2.3 Reporting

Reports should clearly outline the methodologies used and results and include a discussion. All original data should be appended and unmodified. This includes sheets used to record observations and measurements in the field, photographs and original laboratory reporting sheets. Spatial data should be provided.

4 Managing unsuitable rehabilitation

Not all rehabilitated land will have limitations suitable for a beef cattle grazing PMLU. Rehabilitation that is unsuitable for beef cattle grazing will include the following land types:

- Beef cattle grazing PMLU rehabilitation that has been determined to be Class 4 or Class 5 by land suitability assessment
- Native ecosystem-only PMLU rehabilitation, including natural (historic and substitute), hybrid, and novel (planned and unplanned) native ecosystem classes described by Spain et al. (2023).

4.1 Improving the suitability class of unsuitable rehabilitation

Land use limitations (i.e., the inherent properties of the soil and land that are used to assess land use requirements and decide suitability) for beef cattle grazing PMLU rehabilitation are fixed or set when an area of rehabilitation is constructed. Unlike productivity metrics commonly used to assess grazing trials, land use limitations are not easily manipulated by management decisions or inputs and should be considered unchangeable.

For example, if spoil on a dump surface is extremely saline (i.e., ECe >16 dS/m) at the time that topsoil is respread onto it, that spoil will almost certainly remain extremely saline, at least in conceivable timeframes relevant to PRC plan schedules. As soil salinity within the ERD (0-0.6 m depth) is a pasture production limitation, agricultural land evaluation will decide the rehabilitation is unsuitable (i.e., Class 5 (ECe >16 dS/m in ERD) for a beef cattle grazing PMLU).

A possible exception is nutrient deficiency and the amount of Available-P in constructed Anthroposols. If evaluation decides an area of rehabilitation is Class 5 (Available-P <4 mg/kg) or Class 4 (Available-P <8-4 mg/kg) this could be adjusted by fertiliser application to make the rehabilitation suitable (i.e., Class 3 (Available-P >14-8 mg/kg) or better), providing no other severe or extreme limitations are present. Fertiliser applications on grazing pastures may be feasible for a mining company during the rehabilitation monitoring and evaluation phase before rehabilitation is certified (EP Act, s318ZD). However, the economics of applying fertilisers on sown pastures in a post-mining, commercial grazing land use situation is questionable (Lawrence et al., 2015) and not common practice in central Queensland.

These examples highlight the need for geochemical characterisation and selection of suitable materials (i.e., suitable spoils and soils) for use in rehabilitation. New landforms and new soil profiles should be purposefully constructed with known land use limitations and ameliorated as necessary during construction (e.g. with fertiliser and gypsum applications) which are appropriate for beef cattle grazing PMLU requirements. As inherent land use limitations are enduring, beef cattle grazing PMLU rehabilitation should be suitable Class 3 or better on the day it is constructed, at the time of certification, and thereafter.

4.2 Grazing of unsuitable rehabilitation

It may be desirable in some situations to graze unsuitable rehabilitation for commercial (i.e., for profit) or land stewardship (i.e., conservation grazing) reasons. Commercial grazing opportunities may exist when unsuitable Class 4 rehabilitation can be grazed in conjunction with suitable rehabilitation or unmined land, in better seasons, for relatively short periods (i.e., weeks not months). This will require careful management of pastures and grazing, and the stocking rate for the area, to maintain land condition and prevent potential land and water degradation. It will never be appropriate to graze unsuitable rehabilitation in times of drought.

It is unlikely that commercial grazing of unsuitable Class 4 rehabilitation will occur frequently or for periods longer than a few weeks. It will never be appropriate to graze unsuitable Class 5 rehabilitation for commercial purposes. By definition, rehabilitation areas that are determined to be Class 4 or Class 5 by land suitability assessment cannot be sustainably grazed and are unsuitable for a beef cattle grazing PMLU. Consequently, any commercial grazing opportunities should be recognised lower in priority to achieving and maintaining a stable condition (EP Act, s111A).

Grazing of unsuitable rehabilitation may also be desirable for land stewardship reasons. These reasons may include using grazing as a management tool to reduce pasture biomass and bushfire risk, including fire temperature when rehabilitation is burned, or to maintain and increase the biodiversity of groundcover habitat. Cattle grazing is known to be useful for managing invasive and highly combustible pasture grass species (e.g., buffel grass) in unmined landscapes (Lebbink et al., 2023) and may be similarly useful in native ecosystem PMLU rehabilitation where fire-sensitive native species are present (e.g., *Acacia harpophylla,* brigalow). In every situation, this type of grazing will be sub-commercial and short-term, perhaps days or weeks in duration. In some situations, it may not be possible at all due to a lack of accessible water for stock, fencing, and other constraints.

Grazing unsuitable rehabilitation for land stewardship reasons will need to be monitored carefully because overgrazing may cause rapid land degradation (i.e., erosion) and loss of habitat values (e.g., habitat destruction and reduced species richness). Where grazing unsuitable rehabilitation for land stewardship reasons does occur, it should be recognised lower in priority to achieving and maintaining a stable condition (EP Act, s111A).

5 Glossary

AMD	Acid and metalliferous drainage, see INAP (2014).
Anthroposol	Human-made soil, see Isbell and NCST (2021).
ECe	Electrical conductivity from a saturated extracted. EC (1:5 water) is converted to ECe by a multiplier factor based on soil texture, see Hazelton and Murphy (2007).
ERD	Effective rooting depth, the soil depth that can be exploited by plant roots.
ESP	Exchangeable sodium percentage, the amount of exchangeable sodium as a proportion of the sum of all the exchangeable cations, see Hazelton and Murphy (2007).
N	Nitrogen, an essential plant macro-nutrient, playing an essential role in the production of chlorophyll (Hall, 2008).
P	Phosphorus, an essential plant macro-nutrient required for cell division and growth (Hall, 2008).
PAF	Potentially acid forming, material has a significant reducible sulphur content, the acid generating potential of which exceeds the inherent acid neutralising capacity of the material, see AMIRA (2002).
PAWC	Plant available water capacity, the amount of water that soil can store, and which is later available for plant usage.
PMLU	Post-mining land use, has the same meaning as in EP Act, s112.
PRC Plan	Progressive rehabilitation and certification plan, has the same meaning as in EP Act, s112.
Salinity	Soil salinity refers to the accumulation of soluble salts, mainly sodium but also other cations, which may be associated with chlorides and other anions, see Hazelton and Murphy (2007).
Stable rehabilitation	Has the same meaning as in EP Act, s111A.
SD	Standard deviation. In statistics, the standard deviation is a measure of the amount of variation or dispersion of a set of values.
Sodicity	Soil sodicity is concerned with the amount of exchangeable sodium on the cation exchange complex that may lead to dispersion, see Hazelton and Murphy (2007).
3P species	Pasture species that are perennial, productive, and palatable to livestock.

6 References

AMIRA (2002) *ARD Test Handbook Project P387A Prediction & Kinetic Control of Acid Mine Drainage,* AMIRA International Limited.

Australian Government (2016) *Preventing Acid and Metalliferous Drainage,* Commonwealth of Australia. Available: https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-preventing-acid-and-metalliferous-drainage-handbook-english.pdf [Accessed 3 October 2023].

Baker, DE and Eldershaw, VJ (1993) *Interpreting soil analyses - for agricultural land use in Queensland,* Department of Natural Resources and Mines.

Bell, LC, Mulligan, DR, Mitchell, RJ, 1991. Definition of rehabilitation strategies for prestrip Tertiary overburden spoil at the Saraji open-cut coal mine. Progress Report No 2 to BHP-Utah Coal Limited. University of Queensland, Department of Agriculture, Brisbane.

BHP Coal (2017) *BHP Coal, Landform design guideline,* BHP Coal.

Burgess, JW (2003) *Land Resource Assessment of the Windeyers Hill Area, Isaac–Connors and Mackenzie River Catchments, Central Queensland, Volume 1,* Queensland Department of Natural Resources and Mines. Avaialable: https://www.publications.qld.gov.au/dataset/28930c90-725d-4501-8d0e-08b3e40c2ad1/resource/e21c0552-398e-41d2-88f7-ab617a899a5f/download/wdh-qnrm02189-windeyers-hill-land-resource-assessment-vol-1.pdf [Accessed 3 October 2023].

Campbell, C, Haling, R and Guppy, C (2012) 'Critical phosphorus levels for butterfly pea and buffel grass and the impact of inter-specific competition', Proceedings of the 27th Annual Conference of the Grasslands Society of NSW. Available: https://www.grasslandnsw.com.au/FreeContent/2012/17-2012-Campbell.pdf [Accessed 3 October 2023].

Carroll, C, Dougall, C, Silburn, M, Waters, D, Packett, B and Joo, M (2010) '*Sediment erosion research in the Fitzroy basin central Queensland: an overview*', Proceedings of the 19th World Congress of Soil Science, Soil Solutions for a Changing World, 167-170. Available: https://www.iuss.org/19th%20WCSS/Symposium/pdf/2078.pdf [Accessed 3 October 2023].

Carroll, C, Merton, L and Burger, P (2000) 'Impact of vegetative cover and slope on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines', *Australian Journal of Soil Research,* 38**,** 313-27. https://doi.org/10.1071/SR99052.

Carroll, C and Tucker, A (2000) 'Effects of pasture cover on soil erosion and water quality on central Queensland coal mine rehabilitation', *Tropical Grasslands,* 34**,** 254-262. Available: https://www.tropicalgrasslands.info/public/journals/4/Historic/Tropical%20Grasslands%20Journal%20archive/PDFs/Vol_34_2000/Vol_34_03-04_00_pp254_262.pdf

Carroll, C, Tucker, A, Merton, L, Burger, P and Pink, L (2001) *Sustainability Indicators for Coal Mine Rehabilitation*. ACARP project C7006. Australian Coal Association Research Program (ACARP). Available: https://www.acarp.com.au/abstracts.aspx?repId=C7006 [Accessed 3 October 2023].

Cech, PG, Edwards, PJ and Venterink, HO (2010) 'Why is Abundance of Herbaceous Legumes Low in African Savanna? A Test with Two Model Species', *Biotropica,* 42**,** 580-589. Available: https://www.jstor.org/stable/40863794 [Accesed 3 October 2023].

Clewett, JF, Newsome, T, Paton, CJ, Melland, AR, Eberhard, JE, Bennett, JM and Baillie, CP (2021) 'Sustainability of beef production from brigalow lands after cultivation and mining. 3. Pasture rundown, climate and grazing pressure effects', *Animal Production Science*. Avaialble: https://www.publish.csiro.au/AN/pdf/AN20134 [Accessed 3 October 2023].

Dixon, RM, Anderson, ST, Kidd, LJ and Fletcher, MT (2020) '*Management of phosphorus nutrition of beef cattle grazing seasonally dry rangelands; a review*', *Animal Production Science,* 60**,** 863-879. https://doi.org/10.1071/AN19344.

FAO (1976) *A framework for land evaluation,* United Nations, Food and Agriculture Organisation. Available: https://edepot.wur.nl/149437 [Accessed 3 October 2023].

French, AV and Clarke, SP (1993) 'Tropical pasture establishment. 14. Producer extablishment practices and experiences in southern inland Queensland', *Tropical Grasslands,* 27**,** 387-390.

Grigg, A, Mullen, B, Byrne, T and Shelton, M (2007) *Sustainable Grazing on Rehabilitated Lands in the Bowen Basin - Stage 2*. ACARP project C9038 (Stage 2). Australian Coal Research Program (ACARP). Available: https://www.acarp.com.au/abstracts.aspx?repId=C9038 [Accessed 3 October 2023].

Grigg, A, Shelton, M and Mullen, B (2000) 'The nature and management of rehabilitated pastures on open-cut coal mines in central Queensland', *Tropical Grasslands,* 34**,** 242-250. Available: https://www.tropicalgrasslands.info/public/journals/4/Historic/Tropical%20Grasslands%20Journal%20archive/PDFs/Vol_34_2000/Vol_34_03-04_00_pp242_250.pdf [Accessed 3 October 2023].

Grigg, AH, Emmerton, BR and Callum, NJ (2001) *The development of draft completion criteria for ungrazed rehabilitation pastures after open-cut coal mining in central Queensland*. ACARP project C8038. Australian Coal Association Research Program (ACARP). Available: https://www.acarp.com.au/abstracts.aspx?repId=C8038 [Accessed 3 October 2023].

Grigg, AH, Mullen, B, So, HB, Shelton, HM, Bisrat, S, Horn, P and Yatapanage, K (2002) *Sustainable grazing on rehabilitated lands in the Bowen Basin -Stage 1*. ACARP project C9038. Australian Coal Association Research Program (ACARP). Available: https://www.acarp.com.au/abstracts.aspx?repId=C9038 [Accessed 3 October 2023].

Hall, R (2008) *Soil Essentials: managing your farm's primary asset*, CSIRO Publishing.

Harwood, MR, Hacker, JB and Mott, JJ (1999) '*Field evaluation of seven grasses for use in the revegetation of lands disturbed by coal mining in Central Queensland*', *Australian Journal of Experimental Agriculture,* 39**,** 307-16. Available: https://www.publish.csiro.au/an/EA98119 [Accessed 3 October 2023].

Hazelton, P and Murphy, B (2007) *Interpreting soil test results: What do all the numbers mean?*, CSIRO Publishing. ISBN: 978-0-643-09468-0

Henderson, S, Fletcher, G and Richards, B (2004) *Rehabilitation of Dispersive Tertiary Spoil in the Bowen Basin*. ACARP Project C12031. Australian Coal Association Research Program (ACARP). Avaialable: https://www.acarp.com.au/abstracts.aspx?repId=C12031 [Accessed 3 October 2023].

INAP (2014) *Global acid rock drainage guide,* The International Network for Acid Prevention. Avaialble: http://www.gardguide.com/index.php?title=Main_Page [Accessed 3 October 2023].

Irvine, SA and Doughton, JA (2001) '*Salinity and Sodicity, Implications for Farmers in Central Queensland*', Proceedings of the Science and Technology: Delivering results for agriculture? Avaialable: https://www.agronomyaustraliaproceedings.org/images/sampledata/2001/3/b/irvine.pdf [Accessed 3 October 2023].

Isbell, RF and NCST (2021) *The Australian Soil Classification*, CSIRO Publishing. ISBN: 9781486314782.

Jones, RJ (1990) 'Phosphorus and beef production in northern Australia. 1. Phosphorus and pasture productivity - a review', *Tropical Grasslands,* 24**,** 131-139. Available: https://www.tropicalgrasslands.info/public/journals/4/Historic/Tropical%20Grasslands%20Journal%20archive/PDFs/Vol_24_1990/Vol_24_03_90_pp221_230.pdf [Accesed 3 October 2023].

Lawrence, D, Buck, S, Chudleigh, F, Johnson, B and Peck, G (2015) 'Nitrogen fertiliser may pay on tropical grass pastures', Proceedings of the Buidling productive, diverse and sustainable landscapes. Avaialable: http://agronomyaustraliaproceedings.org/images/sampledata/ASA17ConferenceProceedings2015.pdf [Accessed 3 October 2023].

Lebbink, G, Dwyer, J and Fensham, R (2023) 'Managed livestock grazing conservation outcomes in a Queensland fragmented landscape', *Ecological management & restoration,* 22**,** 5-9. Available: https://onlinelibrary.wiley.com/doi/full/10.1111/emr.12460 [Accessed 3 October 2023].

Loch, R (2000) 'Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong, Queensland', *Australian Journal of Soil Research,* 38**,** 299-312. Available: https://www.publish.csiro.au/sr/sr99030 [Accessed 3 October 2023].

Maczkowiack B, Smith C, Erskine P and Mulligan D (2013) ‘Risk Assessment Tools To Support End-Use Decisions for Mined Land of the Bowen Basin’. Available: https://www.acarp.com.au/abstracts.aspx?repId=C19028 [Accessed 3 October 2023].

McClurg, JI (1999) *Soils and Land Suitability of the Gavial-Gracemere Area, Central Queensland*, Department of Natural Resources and Mines. Available: https://www.publications.qld.gov.au/dataset/441b1724-fa90-4580-a300-dd5b82837204/resource/6280cffa-6618-4e08-9d07-09f1402447ef/download/cqg-dnrq990146-gavial-gracemere-soils-and-land-suitability.pdf [Accessed 3 October 2023].

Mckenzie, NJ, Grundy, MJ, Webster, R and Ringrose-Voase, AJ (2008) *Guidelines for Surveying Soil and Land Resources*, CSIRO Publishing. ISBN: 9780643095809.

Melland, AR, Newsome, T, Paton, CJ, Clewett, JF, Bennett, JM, Eberhard, J and Baillie, CP (2021) 'Sustainability of beef production from brigalow lands after cultivation and mining. 2. Acland grazing trial pasture and cattle performance', *Animal Production Science,* 61**,** 1262-1279. https://doi.org/10.1071/AN20134.

Myers C and Robbins G (1991) ‘Sustaining productive pastures in the tropics: 5. Maintaining productive sown grass pastures’, Tropical Grasslands, 104–110, Available at: http://tropicalgrasslands.info/public/journals/4/Historic/Tropical Grasslands Journal archive/PDFs/Vol_25_1991/Vol_25_02_91_pp104_110.pdf.

NCST (2009) *The Australian Soil and Land Survey Field Handbook*, The National Committee on Soil and Terrain, CSIRO Publishing. ISBN: 9780643093959.

Paton, CJ, Clewett, JF, Melland, AR, Newsome, T, Everhard, J, Bennett, JM and Baillie, CP (2021) 'Sustainability of beef produciton form brigalow lands after cultivation and mining. 1. Sown pasture growth and carrying capacity', *Animal Production Science*. https://doi.org/10.1071/AN20134.

Peck, G, Hall, T, Silcock, R, Clem, B, Buck, S and Kedzlie, G (2012) '*Persistance of pasture legumes in southern and central Queensland*', Proceedings of the Capturing Opportunities and Overcoming Obstacles in Australian Agronomy. Available: http://www.agronomyaustraliaproceedings.org/images/sampledata/2012/8218_6_peck.pdf [Accessed 3 October 2023].

Queensland Government (1990) Guidelines for Agricultural Land Evaluation in Queensland, Land Resources Branch & Department of Primary Industries. Available: https://www.publications.qld.gov.au/dataset/bf5588bc-a0ee-4e1b-ab09-dc69e4e5680a/resource/d6591386-08e2-453f-a6fa-dff2a756215f/download/qldguidelinesforagriculturallandevaluation2e2015.pdf [Accessed 3 October 2023].

Queensland Government (1995) Land suitability assessment techniques, Department of Mines and Energy.

Queensland Government (2013) Regional land suitability frameworks for Queensland, Department of Natural Resources and Mines & Department of Science Information Technology Innovation and the Arts. Available: https://www.publications.qld.gov.au/dataset/bf5588bc-a0ee-4e1b-ab09-dc69e4e5680a/resource/865d2e71-39e3-4db8-92bd-5fc9bc2956be/download/regionallandsuitabilityframeworks.pdf [Accessed 3 October 2023].

Queensland Government (2015) Guidelines for Agriculture Land Evaluation in Queensland, Department of Science Information Technology and Innovation & Department of Natural Resources and Mines. Available: https://www.publications.qld.gov.au/dataset/bf5588bc-a0ee-4e1b-ab09-dc69e4e5680a/resource/d6591386-08e2-453f-a6fa-dff2a756215f/download/qldguidelinesforagriculturallandevaluation2e2015.pdf [Accessed 3 October 2023].

Queensland Government (2022) 2021-22 Report, Queensland Mine Rehabilitation Commissioner, Office of the Queensland Mine Rehabilitation Commissioner. Available: https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0023/303791/qmrc-2021-22-annual-report.pdf [Accessed 3 October 2023].

Raine, SR and Loch, RJ 2003. What is sodic soil? Idntification and management options for constuction sites and disturbed lands. *Workshop on soils in rural Queensland.* Toowoomba.

Rietkerk, M, Ketner, P, Burger, J, Hoorens, B and Olff, H (2000) 'Multiscale soil and vegetation patchiness along a gradient of herbivore impact in a semi-arid grazing system in West Africa', *Plant Ecology,* 148(2)**,** 207-224. Avaialble: https://link.springer.com/article/10.1023/A:1009828432690 [Accessed 3 October 2023].

Russell, JS, 1976. Comparative salt tolerance of some tropical and temperate legumes and tropical grasses. Australian Journal of Experimental Agriculture and Animal Husbandry, 16(78), 103-109. https://doi.org/10.1071/EA9760103.

Shields, PG and Williams, BM (1991) Land resource survey and evaluation of the Kilcummin area, Queensland, Department of Natural Resources and Mines. Available: https://www.publications.qld.gov.au/dataset/3a80e860-0759-4fde-a0d7-

a6fb80b89fef/resource/327b4ea3-523b-4528-9419-9b793c05716a/download/kcm-qv91001-kilcummin-area-land-resource-survey.pdf [Accessed 3 October 2023].

So, HB, Sheridan, GJ, Loch, RJ, Carroll, C, Willgoose, G, Short, M and Grabski, A (1998) *Post Mining Landscape Parameters for Erosion and Water Quality Control*. ACARP Project C4011. Australian Coal Research Program (ACARP). Available: https://www.acarp.com.au/abstracts.aspx?repId=C4011 [Accessed 3 October 2023].

Spain, C, Nuske, S, Gagen, E and Purtill, J (2023) Evaluating native ecosystem rehabilitation options in Queensland, Office of the Queensland Mine Rehabilitation Commissioner. Available: https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0021/303438/evaluating-native-ecosystem-rehabilitation-options-in-qld.pdf [Accessed 3 October 2023].

Thomas, RJ, 1995. Role of legumes in providing N for sustainable tropical pasture systems. Plant Soil 174, 103–118. Available: https://link.springer.com/article/10.1007/BF00032243 [Accessed 3 Oct

Vacher, CA, Raine, SR and Loch, RJ (2004) '*Strategies to reduce tunnelling on dispersive mine spoil materials*', Proceedings of the 13th International Soil Conservation Organisation Conference - Conserving Soil and Water for Society: Sharing Solutions. Available: https://topsoil.nserl.purdue.edu/isco/isco13/PAPERS%20R-Z/VACHER%202.pdf [Accessed: 3 October 2023].