Office of the **Queensland Mine Rehabilitation Commissioner**

A review of research and tools for grazing as a post-mining land use in Queensland

Technical paper

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Disclaimer

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Contents

Tables

Executive Summary

Grazing is commonly nominated as a post-mining land use (PMLU) in Queensland. A review of progressive rehabilitation and closure plan (PRC plan) schedules approved up to the 7th of November 2023 found that the overwhelming majority of mines had some land allocated to grazing as a PMLU. Despite its prevalence, leading practices for establishing and demonstrating grazing as a PMLU are not clearly defined. Additionally, the objectives of grazing as a PMLU are not often specified in planning documents, making it challenging to set clear goals and demonstrate success. To improve these practices, we reviewed the international, national, and Queensland-specific literature related to grazing PMLUs, and present that review here. The primary focuses of this review were to elucidate the objectives for grazing as a PMLU, describe key considerations when planning for grazing and outline methods to demonstrate successful grazing rehabilitation.

Our review found that the objectives for grazing on rehabilitated mined land vary. For example, some land had conservation grazing as an objective or utilised grazing for land management purposes. Examples of commercial grazing were also identified within the literature, and focussed on pasture productivity, commercial feasibility, and live weight gain. These commercial objectives were generally the focus of Queensland-based research.

The review also revealed a body of research which evaluated key considerations and risks when rehabilitating mined land to a grazing PMLU. Studies considered the stability and safety of the landform, erosion, impacts of heavy metal contamination on grazing animals and resilience of grazing lands. In the Queensland-based literature, we found that although some final milestone criteria had been recommended, proponents had generally not adopted them in historic planning documents. Consequently, we highlight recent advice provided by the Office of the Queensland Mine Rehabilitation Commissioner (OQMRC) which adapts Land Suitability Assessment criteria for grazing lands to mined lands of the Bowen Basin, further underscoring the availability of well evidenced final milestone criteria for grazing PMLU areas in Queensland.

Additionally, it is required that land is made safe, stable, and non-polluting after mining. A PMLU should also be viable and sustainable in the long term. Our review of available resources related to grazing showed that in Queensland there are many existing agricultural surveying, monitoring, and modelling tools that have been developed for conventional grazing practices. These tools could be used to demonstrate that land is safe, stable, and non-polluting, and can sustain a grazing PMLU. Therefore, this review includes a discussion of the features of these tools and how they could be used to assess rehabilitation to grazing in Queensland.

Our exploration of the assessment tools available to demonstrate that rehabilitated grazing could achieve a safe, stable and non-polluting state includes discussions on landform design, Land Suitability Assessment, Land Capability, and agricultural land classification. This section includes discussion of previous work from the OQMRC which has adapted the Land Suitability Assessment to rehabilitated grazing lands in the Bowen Basin.

Our comparison of the tools which could be used to demonstrate that the rehabilitation could sustain a grazing PMLU includes the following monitoring tools: Land Condition Assessment Tool (LCAT), Stocktake, Landscape Function Analysis (LFA), VegMachine; and the modelling tools: GRASP, FORAGE Long Term Carrying Capacity (LTCC), AussieGRASS, and SWIFTSYND. Our discussion of these tools highlights the benefits and limitations of each within the context of mined land rehabilitated for a grazing PMLU. We also discuss the management implications of grazing rehabilitated mined land and describe the benefit of ensuring that these management implications are communicated to the subsequent landholder or relevant grazier.

A discussion of the reviewed literature and available tools reveals several knowledge gaps concerning grazing as a PMLU. One such gap is that the objectives for grazing land were often poorly articulated (e.g., commercially viable vs. grazing as a land management tool). We also propose that these uncertainties, in a Queensland context, may be related to the lack of clarity regarding objectives and final milestone criteria of the PMLUs. Furthermore, our literature review underscores a lack of long-term grazing trials pertaining to the stability of grazed rehabilitated landforms. These uncertainties in how to demonstrate stable and successful rehabilitation of mined land for grazing may be mitigated by employing the tools presented in this document and adaptively managing the land.

Grazing is the most common PMLU in Queensland, and this report seeks to improve understanding of planning and management practices for rehabilitation with a grazing PMLU. Readers are encouraged to consider this report in conjunction with other technical papers regarding rehabilitation to grazing produced by the OQMRC.

1 Introduction

Grazing is a common post-mining land use (PMLU) in Queensland and further afield. There are numerous proposed reasons for this, such as the economic benefits from grazing post-mining areas (Skousen and Zipper, 2014), the perceived ease and low cost of rehabilitating to this use (Skousen and Zipper, 2014; Kragt and Manero, 2021), and the consistency of grazing with community expectations and/or pre-mining land uses (Fogarty et al., 2019). Practices to rehabilitate mined land to a grazing land use vary across regions due to various reasons, including different operator policies, landscapes and community expectations (Etter, 1973; Paton et al., 2021; Petra Diamond Mines, 2022).

Due to clearing of native forest for cattle grazing between 1963 and 1976 in the Bowen Basin, a large part of mined land in Queensland was used for grazing before resource activity approval, and therefore grazing is a common PMLU in the state (Short, 2023). Historically, Environmental Authorities (EAs) have reflected the request of EA holders to return mined land to grazing (Trevaskis and Trotter, 2022), as do some newly approved progressive rehabilitation and closure plan (PRCP) schedules. For example, 25/28 mining projects with approved PRCP schedules contain at least one rehabilitation area with plans for a grazing PMLU, covering ~29,000 ha across those 25 mining leases (according to a survey of progressive rehabilitation and closure (PRC) plans up until 7 November 2023).

While the proportion of post-mining land areas likely to be returned to grazing is significant (~75% of the area of post-mining land in approved PRC plans to date), the limitations of the land after cessation of mining may complicate the success of the PMLU. For example, the fact that grazing is often a means to produce livestock for human consumption (Hunt et al., 2014) means that examining remediation practices and management regimes to achieve this type of use requires careful and considered attention (Sutherland et al., 2016).

This review considers international, interstate and local research on mine rehabilitation to a grazing PMLU. It discusses the different types of grazing highlighted in the literature and their relevant requirements. It is of note that most planning documents in Queensland specifically refer to cattle grazing, and although sheep grazing is present in the state (Johnston et al., 2000), this review is therefore centred around cattle grazing. This document does however address other types of grazing, examines the key considerations for rehabilitating to these uses and identifies successful and unsuccessful rehabilitation scenarios. We go on to consider learnings from those scenarios and how they apply to Queensland.

Furthermore, rehabilitation to a grazing PMLU requires demonstration of success against milestone criteria (also known as completion criteria). These final milestone criteria encompass:

- demonstration of a safe, stable and non-polluting landform, and
- demonstration that the land can sustain grazing as a PMLU.

As such, the review also explores existing tools developed for the agricultural sector in Queensland which could be used to demonstrate the achievement of landforms which are safe, stable and non-polluting and can sustain a grazing PMLU.

Contemporary leading practice to demonstrate these characteristics requires thoughtful planning, assessment and monitoring of the rehabilitation. Consequently, this review aims to guide the development of leading practice for rehabilitating mined lands to grazing in Queensland alongside other technical papers published by the Office of the Queensland Mine Rehabilitation Commissioner (OQMRC) (Short, 2023; Short and Bourne, 2023). In Short (2023) the Land Suitability Assessment framework was adapted for mined land with a cattle grazing PMLU in the Bowen Basin, and in Short and Bourne (2023) a step by step guide for planning for an operational grazing enterprise on mined land is presented. This review complements the aforementioned technical papers by highlighting broader considerations for grazing as a PMLU and focusses on approaches to achieve and demonstrate successful rehabilitation.

2 Previous rehabilitation to grazing research

To understand the objectives and key issues pertaining to the establishment of grazing on rehabilitated land, a literature review was performed. Studies of grazing on mined land internationally, nationally, and within Queensland were found in the academic and grey literature, and spanned the

USA, Canada, South Africa, Ireland and Australia. This diverse geographic scope provides insights into regional differences regarding the objectives of grazing on mined land, and highlights scenarios in which non-commercial and commercial grazing is the PMLU.

Studies pertaining to rehabilitation to grazing included grazing trials, risk assessments, stakeholder surveys and rainfall simulations, and are summarised in Appendix Table 1. The studies reviewed encompass a range of research aims, including assessing community aspirations, animal production, landform stability, contamination, and grazing-associated ecology. These themes highlight that some research projects focus on whether the land is safe, stable and non-polluting, whilst others focus on the sustainability of the PMLU, i.e., the productivity of grazing operations on previously mined lands.

2.1 Non-commercial or resource management objectives for grazing rehabilitation

Certain international rehabilitation projects utilise grazing for non-commercial uses, such as conservation grazing, or as a tool for natural resource management. In Canada, rehabilitated mined land has been successfully used to increase the habitat of the wood bison (The Mining Association of Canada, 2021). Similarly, plans to graze bighorn sheep on rehabilitated mined land in Canada, prompted an investigation of appropriate foraging species (Etter, 1973). In both cases, the target animals for conservation grazing have been threatened by hunting and habitat loss (according to iucnredlist.org). In this review, no examples were found where grazing on rehabilitated mined land was undertaken for conservation purposes in Australia.

Grazing may also be used as a tool for natural resource management on mined land. For example, the Finsch Diamond Mine in South Africa attempted to rehabilitate its lands to Savannah and Nama-Karoo, a native shrubland. The rehabilitation was deemed to not be "blending into the surrounding environment" and therefore the area was grazed to uncompact the ground and improve seed germination, with grazing management determined through biomass and carrying capacity calculations (Petra Diamond Mines, 2022). Furthermore, grazing may reduce fire risks by decreasing fuel amounts, contributing to the safety of the rehabilitation area (Davies et al., 2022).

In the Australian-based literature, it is also recognised that grazing can improve pasture productivity (Meat and Livestock Australia, 2021; Glencore, 2023a), Furthermore, carefully managed grazing can be used to establish certain vegetation communities and introduce carbon into the soil, ultimately improving the functionality of the pasture (Trevaskis and Trotter, 2022).

Aside from examples of conservation grazing and grazing for natural resource management, there are also instances in which the ecology of grazing on rehabilitation areas has been studied, highlighting that commercial pasturelands are often considered to have environmental value. For example, Steward (2006) highlights that well managed grazing rehabilitation can provide "diversification of the vegetation, increased rate of soil development, reduction of undesirable species, and enhancement of wildlife habitat". Conversely, Zipper and Skousen (2021) describe how grazing may play a role in the introduction of invasive plants and impact wildlife on grazing rehabilitation, and therefore the ecological outcomes associated with grazing as a PMLU are a consideration. Similarly, Griffiths and Rose (2017) showed that rehabilitation pastures had less (87-107) native plant species diversity than natural pastures (144-174), although the authors still described the numbers of native plant species in both types of site as "high". Thovhakale (2010), however, highlights that in a South African context, grazing rehabilitated mined land did not significantly impact biodiversity, albeit over a relatively short term of less than two years.

Policy regarding the reclamation of mined land in Wyoming distinguishes between two land types: "grazingland", which is native vegetation in rangeland and forest actively managed for grazing and "pastureland", which produces "adapted, domesticated, forage plants to be grazed by livestock". These land types are distinguished through their pasture composition (% introduced perennial exotics), how intensive their grazing use is and whether they are intended for use by wildlife in addition to a grazing/hay production use (Wyoming Department of Environmental Quality, 2014).

In Queensland, plans to integrate ecological outcomes with grazing rehabilitation have also been explored. Trevaskis and Trotter (2022) aimed to develop a conceptual silvopastoral model for sustainable cattle grazing on mined land in the Bowen Basin which involved integrating trees or woody vegetation with pasture for ecological and economic benefits. This study made recommendations as to how a silvopastoral model could be established to improve productivity of grazing enterprises on mined land or land adjacent to mined land. This research therefore shows that non-commercial, ecological objectives and commercial grazing objectives may co-exist on the same parcel of rehabilitated land.

2.2 Commercial objectives and animal production considerations

Various documents in the grey and academic literature have measured or discussed aspects of commercial cattle grazing on rehabilitated mined land. This includes the USA's Surface Mining Control and Reclamation Act 1977 (SMCRA) which emphasises restoring land to support its pre-mining level of use or better. Therefore, if the land was commercially grazed prior to mining, there is an expectation that rehabilitation to cattle grazing would be at least as economically productive as pre-mining grazing. However, an example from the USA underscores the difficulties of establishing a productive grazing enterprise on rehabilitation. Teutsch et al. (2008) highlight challenges in animal production, namely limitations in livestock densities on rehabilitation with pasture established on spoil in the USA.

In Australia, some research has highlighted the feasibility of rehabilitation to grazing across different areas, within Queensland and other states. Griffiths and Rose (2017) present a New South Wales based study of grazing on mined land and demonstrate that careful grazing management and rehabilitation practices can lead to desirable animal production outcomes. Similarly, recent research of mined land in Queensland has used GRASP modelling, a type of pasture modelling, to assess the sustainability and economic feasibility of cattle grazing on rehabilitated lands in the Toowoomba region (Clewett et al., 2021). A similar grazing trial was performed in the Bowen Basin, assessing pasture productivity and stocking rates (Grigg et al., 2002).

Overall, a comparison of these grazing trials found that the grazing rehabilitation in the Toowoomba region may be more suited to commercial cattle grazing than the Bowen Basin. Clewett et al. (2021) found that rehabilitated lands in the Toowoomba region had higher pasture growth than unmined areas, leading to increased beef production and economic returns. Another study conducted cattle grazing trials and evaluated root penetration and soil properties in the Toowoomba region (Melland et al., 2014). Similarly, it found little difference between rehabilitated and control sites in terms of benefits or constraints to pasture production, except for higher plant-available phosphorus (P) in some rehabilitated sites. Both of the grazing rehabilitation research projects conducted in the Toowoomba region emphasise the potential for successful grazing on rehabilitated lands.

It is however noted that the Toowoomba region is somewhat dissimilar to the main coal mining area in Queensland, the Bowen Basin, with regards to the parameters which influence grazing productivity. Grazing trials in the Bowen Basin showed a sustainable stocking rate of ~ 3.7 ha/head over the experimental period (during the growing season)(Grigg et al., 2002), which was higher than rehabilitation areas in the Toowoomba region (on average, 2 ha/head) (Clewett et al., 2021), reflecting that the land in the main mining region was more limited than that of the Toowoomba region. This is likely due to the differences in climatic and soil characteristics, which in the Toowoomba region tend to be suited to grazing (Clewett et al., 2021), whereas the Bowen Basin presents a climate with erratic rainfall and erodible vertosols and sodosols with shallow topsoil (Maczkowiack et al., 2009) which may be a risk to productive grazing on both unmined and mined land. Whether the Bowen Basin grazing trial derived stocking rates for mined land are economically feasible and sustainable was unable to be assessed as the authors stated that more data was required (Grigg et al., 2002).

As the examples from the Toowoomba region and Bowen Basin show, it appears that in the literature, rehabilitation to grazing in Queensland is mainly concerned with commercial grazing objectives. The support to use grazing as a PMLU on the grounds of commercial viability is further exemplified by an example of how productivity targets were used to achieve certification of grazing rehabilitation in Western Australia, as shown in the box on the next page.

Example of accepted achievement of final milestone criteria in a Western Australian mine

The government of Western Australia (WA) has accepted some previously mined land (mineral sands mining) which was rehabilitated to grazing land. According to personal communication from the Department of Mines, Industry Regulation and Safety (DMIRS), the landholder signed a Deed of Acknowledgement and Waiver in 2008 acknowledging that the Iluka mine had been rehabilitated to the landholder's requirements. This source confirmed that there were closure objectives and final milestone criteria that included aspects of public safety, radiation levels, weeds, groundwater quality and levels, restoration of surface water flows and pasture productivity. For this mine, the final milestone criteria regarding pasture productivity included soil fertility as measured by carbon and nutrient levels, pasture composition and a dry weight equivalent of pasture comparable to district averages. It was stipulated that pasture productivity monitoring was to occur every four to six weeks during growing season, over a period of five years (DMIRS, personal communication). These final milestone criteria and monitoring requirements highlight that in the Western Australian scenario, the objectives for the land were not only to be "safe, stable and non-polluting", but also to show sustained productivity of the grazing PMLU.

2.3 Experimental design

Within the literature various documents discussed how grazing trials on mined land should be designed. This discussion focussed primarily on statistical approaches and the choice of reference, analogue or control sites.

As in the above example from WA and various studies concerned with the commercial viability of grazing on rehabilitated land, reference, control and analogue sites are sometimes compared to land rehabilitated to grazing. There are, however, different opinions on how to select analogue, control or reference sites. For example, Cox et al. (2021) proposes that analogue and reference sites should encompass a range of soil types, pasture compositions, management practices and grazing strategies (Cox et al., 2021). While this may mean that reference sites are realistic, in order to achieve sustainable rehabilitation to grazing, reference sites must be safe, stable, non-polluting and able to sustain the PMLU. For example, a reference site which is managed unsustainably, with unsuitable soil characteristics, and which has erosion issues will not be an appropriate analogue as it establish undesirable standards for the rehabilitation.

Furthermore, Sutherland et al. (2016) argue that reference sites must be similar to rehabilitated sites in all respects aside from whether they have previously been mined or not in order to be considered true controls and allow comparison of "like for like". For example, they should have the same climatic conditions, be sown with the same pasture mix and have the same amount of fertiliser applied prior to the commencement of trials. Similarly, the Australian Government sets out that control sites should be similar in all respects aside from the measured condition, in this case mined versus unmined (Australian Government, 2016a). This source also outlines that typical grazing use related parameters to be measured at these sites include "carrying capacity of paddocks, grazing trials, pasture production, weeds and pests" (Australian Government, 2016a). Reference sites for native ecosystem rehabilitation, as described in Australian Government (2016a), are not required to be exactly the same in all ecological characteristics, but instead should "give an indication of the replacement of ecological values over time and likely long term sustainability". For grazing, this may mean that reference sites should show resilience and long term sustainability of the use.

As such, care must be taken when interpreting commercial feasibility studies as the selection of unmined control or reference sites informs the conclusions drawn. For example, Clewett et al. (2021) compared rehabilitated mined land to several unmined sites, including native pastures and pasture-sown retired cropping land, and concluded that the rehabilitated land was more productive than the retired areas of cultivation but comparable to the remaining unmined pastures, highlighting the distinctions between the different reference site types.

In addition to an appropriate choice of reference, control, or analogue site(s), the literature discusses the need for sound statistical principles to underpin experimental design of grazing trials on rehabilitated land. For example, the Leading Practice Sustainable Development Program for the Mining Industry outlines that trials and monitoring programs should consult statistical experts during the planning phase and be based upon statistical principles (Australian Government, 2016a). A sound statistical foundation will help to avoid bias, pick appropriate sample sizes and sampling frequencies, and plan for robust analyses (Australian Government, 2016a). To interpret grazing trials correctly, the number of replicate paddocks and cattle will need to be sufficient to have statistical power, as the alternative is merely the reporting of background error (Sutherland et al., 2016). All in all, grazing trials should undergo rigorous experimental design and employ proper controls as to not undermine the interpretation of their results.

2.4 Alignment with community aspirations

Understanding community aspirations is also deemed important for determining rehabilitation objectives. Guidelines such as the ICMM “Integrated Mine Closure Good Practice Guide” (ICMM, 2019) and Queensland’s PRC plans guideline (Department of Environment and Science, 2021) stress the importance of consulting with communities regarding PMLU selection. Stakeholder engagement in Queensland highlights the significance of early planning with input from the community, monitoring of rehabilitation areas, clear communication of caveats associated with the land and trials to ensure the use is appropriate for the future landholder (Everingham et al., 2018; Rolfe et al., 2018). A Ugandan case study describing grazing of a post-mining landscape underscores the negative outcomes when community consultation is lacking, emphasising the importance of involving local communities in mining and rehabilitation planning (Rugadya, 2020). For example, rehabilitation works were poorly executed for a grazing PMLU, however, livestock were introduced into the post-mining landscape, causing injury and death to stock (Rugadya, 2020).

In addition to the example above, various Australian mining operations aim to achieve grazing outcomes which align with community aspirations. According to Glencore, the purpose of (grazing) rehabilitation in their Australian operations is “to meet government regulations, approval requirements and community expectations” (Glencore, 2023a). Meanwhile, various PRC plans underscore that the community is encouraging of the instatement of grazing as a PMLU. Although not explicitly stated, various Queensland-based grazing trials highlight live weight gain (Appendix Table 1), implying that successful grazing rehabilitation will support commercial grazing activities. Commercial objectives may align with community aspirations, especially in primarily agricultural regions such as the Bowen Basin. While achieving acceptable outcomes for the community is important, the pursuit of a commercially viable grazing operation on rehabilitated mined land must not take precedent over the land being safe, stable and non-polluting (Short, 2023).

2.5 Landform stability

Various studies have explored the safety and stability of rehabilitated landforms under grazing scenarios. In the USA, rainfall simulations and trials comparing different management practices (burnt, and light, medium and heavy grazing) were performed on rehabilitated mined land (Hofmann and Ries, 1991). This study found that groundcover was the most important factor in preventing erosion for all treatments and that burnt land and heavily grazed rehabilitated pastures were the most prone to high levels of erosion, contrasting with ungrazed treatments which had no or minimal erosion (Hofmann and Ries, 1991). These trials show that management of the landform is crucial to the success of the rehabilitation, and that management of grazing in the area may cause or exacerbate stability issues within the rehabilitation areas.

In Queensland, trials studying erosion on grazed mined land have also been performed. Similarly, some of the biophysical limitations of rehabilitated lands across Queensland’s Bowen Basin have been characterised via rainfall simulations at the Blackwater and Goonyella mines, which showed that grazing-related erosion posed a considerable risk to the stability of the land (Grigg et al., 2002) (Appendix Table 1). Consequently, the authors recommended maintaining at least 70% groundcover to prevent erosion (Grigg et al., 2002). An extension of the study presented in Grigg et al. (2002) identified pasture moisture retention as a key to pasture productivity (Grigg et al., 2006), thus linking rainfall and its importance to groundcover and erosion. In a different study, grazing trials at New Acland, in the Toowoomba Region, showed that abiotic properties of rehabilitated soils fell within the range of unmined soils and supported viable pasture production (Bennett et al., 2021). However, this study indicated that the soil types recovered from mined lands were susceptible to erosion and even severe erosion (Bennett et al., 2021). At New Acland, erosion trials via rainfall simulation or using other techniques were not performed, and the erosion study in the Bowen Basin was limited to 30 minute rainfall simulations (Grigg et al., 2002). Meanwhile, the need for validation studies to establish protocols for rainfall simulation trials has been recognised (Dunkerley, 2021). This review did not identify trials in Queensland which studied erosion in the field with natural rainfall and real grazing pressure. Therefore, the landform, soil types and climate should be carefully considered when planning for grazing, and stringently monitored to be able to act early and rapidly in the case of erosional instability (Australian Government, 2016a). The results of these studies also show that the processes by which grazing may affect landform stability over the long-term may not have been quantified comprehensively.

Despite limited scientific erosion trials on land rehabilitated to a grazing outcome, erosion risks are well known to stakeholders in Queensland. In a survey, Bowen Basin based stakeholders identified “surface soil erosion, sub-surface soil erosion, bushfires, weeds and feral animals” as physical risks of grazing as a PMLU (Maczkowiack and Smith, 2012). Models were then created to highlight factors which influenced these risks the most. Rainfall erosivity, soil erodibility, topography, and vegetation cover influenced surface erosion the most in the risk model (Maczkowiack and Smith, 2012). Similarly, another study also found that risk is likely lower if “land is biophysically suitable and of a commercially viable size” (Maczkowiack et al., 2012). Importantly, Maczkowiack and Smith (2012) also underscored the importance of adaptive management and co-operative grazier attitudes as key factors in preventing risks to the stability of the landform.

It is also noteworthy that post-surrender, rehabilitated grazing land will be subject to local stability and erosion-related regulations. For example, grazing enterprises on mined land in the Burdekin, Fitzroy, Wet Tropics, Mackay, Whitsunday, and Burnett Mary regions in the Great Barrier Reef catchment will be subject to the Agricultural ERA standard for Beef cattle grazing in the Great Barrier Reef catchment. These regulations have been developed to combat the impacts that grazing associated erosion can have on water quality and reef health (Office of the Great Barrier Reef, 2022). The supporting information for these regulations highlights the negative impacts of sedimentation from agriculture on the Great Barrier Reef (Office of the Great Barrier Reef, 2022). This information, alongside the literature highlighting how grazing mined land is a risk to landform stability (Grigg et al., 2002), show that improperly managed grazing of previously mined areas may lead to erosion and negatively impact the downstream environment. Ensuring that the grazing rehabilitation will be compliant with local regulations upon surrender will therefore also be important to demonstrate its sustainability.

2.6 Soil contamination

In order for the land to be safe and able to sustain the PMLU, the rehabilitated land must not present a risk of contamination to grazing animals. Contaminant exposure to grazing animals can be via direct contact with contaminated soil, ingestion of contaminated soil as well as the ingestion of contaminated water by livestock (Ng et al., 2014). While animal production is important, the safety of the resulting products to consumers is also a consideration of rehabilitating mined land to grazing. There are examples where mine rehabilitation areas have been deemed unsuitable for grazing due to elevated levels of contaminants. For example, in Jamaica, bauxite mines were rehabilitated to beef cattle grazing to combat national food insecurity, but concerns arose due to soil contamination (Bounds, 1974). Similarly, studies have shown cattle in Canada and Ireland experiencing health issues due to soil heavy metal contamination from mining (Aslibekian and Moles, 2003; Steinke and Majak, 2003). In Queensland, trials on rehabilitated mine tailings have revealed the potential for issues with arsenic and lead accumulation in animal tissue to arise if grazed on certain mined lands for long periods of time (Ng et al., 2014). To produce animal products on previously mined land, there may be a need to assess and remediate contaminants present in the soil, choose plants which do not excessively accumulate toxicants and manage grazing regimes to limit exposure to contaminated soils (Ng et al., 2014). Furthermore, Ecological Investigation Levels (EILs) for contaminated soils are described in the National Environment Protection Measures (NEPM, 2013). Although contaminated land is an issue in rehabilitation to grazing, we did not find examples of contamination from coal mines impacting livestock in the peer reviewed literature.

2.7 Resilience

An additional goal of the rehabilitation may be resilience to major disturbance, such as drought, flood, and fire (Huang et al., 2022). Whether resilience is an element of sustainability is a debated topic (Marchese et al., 2018), but it is logical that a PMLU may only be deemed sustainable if it can demonstrate a certain level of resilience. The resilience of pastures may be considered especially important given recent “extreme” weather events in the state (Hughes et al., 2020). This discussion is of relevance to the Queensland context given that rehabilitated land must be able to sustain a PMLU (*Environmental Protection Act 1994* (Qld) (EP Act), s111A).

Factors which contribute to resilience of grazing rehabilitation include self-sustenance of the pasture (i.e., the capacity of the vegetation to reproduce and replace itself upon senescence, fire and/or drought), rainfall and climatic variables (Audet et al., 2013), diversity of pasture species (Tracy et al.,

2018) and soil water retention (Ngugi et al., 2015). Self-sustenance of the pasture is particularly important for “high-risk” mine sites which rely upon vegetation cover for erosional stability (Hancock et al. 2020). Additionally, it is unknown whether grazing systems established on rehabilitated lands will persist over future decades and how they will recover from fire (Hancock et al., 2020). To avoid a legacy of a risk-prone, unsustainable landform and pasture, monitoring and adaptive management for a certain degree of resilience may be considered leading practice.

2.8 Recommendations in the literature

Findings across international and Australian studies collectively suggest that successful grazing on rehabilitated mined lands requires careful management. It is likely that this management may require adaptation to the specific social and environmental circumstances of rehabilitation areas. Recommendations presented in the literature include careful plant species selection (Etter, 1973; Trevaskis and Trotter, 2022), grazing management (Clewett et al., 2021; Short and Bourne, 2023), and ongoing monitoring to ensure the sustainability of the use (Grigg et al., 2001; Trevaskis and Trotter, 2022).

Issues associated with grazing on rehabilitated land highlighted in the literature include that the activity, if not planned, executed and managed properly may jeopardise the stability of the landform. In 2001, some final milestone criteria were put forward specifically for cattle grazing rehabilitation in the Bowen Basin to attempt to prevent failure of the landform and promote sustainable grazing (Grigg et al., 2001). The criteria include achieving and maintaining sufficient vegetation cover, slope grades, soil properties, and rootzone salinities. While these criteria provide practical advice for successful rehabilitation, and various EAs contain the parameters recommended by Grigg et al. (2001), comparison of the recommended completion criteria in Grigg et al. 2001 and those in EAs presented in Trevaskis and Trotter (2022), found that the recommended values for parameters such as slope and groundcover have not always been adopted by proponents. To ensure viable and productive grazing outcomes, the review by Trevaskis and Trotter (2022) recommended that both the livestock industry and miners collaboratively develop landform design, completion criteria, and grazing management strategies.

3 Current Queensland tools to achieve a grazing PMLU

To develop leading-practice advice it may be of use to explore existing tools which have been developed to show that the land is stable. In particular, the Office of the Queensland Mine Rehabilitation Commissioner (OQMRC) has recently explored how to assess the suitability of rehabilitated land for a grazing PMLU using the Queensland Government’s Land Suitability Assessment, with the objective of encouraging rehabilitation of land to a stable outcome (Short, 2023). In this vein, in Queensland, there are tools to demonstrate that land is safe, stable and non-polluting, and that it can sustain the PMLU, and therefore it may be beneficial to discuss their main traits and how they could be implemented to assess rehabilitation to grazing.

Consequently, this review reflects on how milestones may be determined and goes on to describe and compare land assessment tools for rehabilitation to grazing on mined land. More specifically, it highlights tools which demonstrate:

- that the land is safe, stable and non-polluting, and
- that the land can sustain the PMLU.

In doing so, this review also reflects on current practices and identifies knowledge gaps in how to achieve and demonstrate the success of a grazing PMLU.

3.1 Rehabilitation milestones and methods to derive them

Once a PMLU is chosen, milestones must be described to guide rehabilitation efforts. Rehabilitation milestones are significant events or steps to achieve the rehabilitation objectives. Example milestones are provided in the PRC guideline (Department of Environment and Science, 2023, Appendix 3). Reference milestones of relevance to a grazing PMLU include “landform development and reshaping/reprofiling”, “surface preparation”, “revegetation”, “achievement of surface requirements”, and “achievement of post-mining land use to stable condition” (Department of Environment and Science, 2023, Appendix 3).

Defining milestones and final milestone criteria which include quantitative parameters indicative of an appropriate land condition for grazing improve rehabilitation outcomes. Developing milestone criteria for each milestone must follow SMART criteria: i.e., they are Specific (it is clear what must be done), Measurable, Achievable, Reasonable/relevant (there is a clear connection between the milestone and the desired outcomes) and Time specific (it is clear when the milestone will be completed) (Department of Environment and Science, 2021). Quantitative milestone criteria will give proponents demonstrable goals to track rehabilitation towards and if robustly supported by scientific evidence, will increase confidence in the acceptability of rehabilitated grazing land.

Tools which can be used to demonstrate that the rehabilitation is safe, stable, non-polluting, and can support a grazing PMLU may be useful in developing milestones and criteria via their in-built quantitative benchmarks and methodologies. Tools have been successfully applied in agricultural contexts in Queensland are presented in Appendix Table 2 alongside relevant reference milestones.

3.2 Demonstrating that the grazing rehabilitation is safe, stable and non-polluting

The first step to achieve rehabilitation to grazing after mining is construction of a post-mining landform and surface which will be able to support pasture vegetation and be appropriate for grazing. Various tools exist to develop and demonstrate acceptability of different facets of the post-mining landform. These tools include landform design, Land Suitability Assessment, Land Capability, and agricultural land classification.

The OQMRC has previously published work on using Land Suitability Assessment to demonstrate that grazing is safe, stable, and non-polluting (Short, 2023) and landform design to plan for rolling pasture landscapes (Short and Bourne, 2023). While Land Suitability Assessment is esteemed the most suitable tool to demonstrate that the land is safe, stable and non-polluting, and its achievement will be supported by good landform design, the OQMRC recognises that other land assessment tools have been used by rehabilitation professionals. To comprehensively review the available tools, they are presented here.

3.2.1 Landform design

Landform design is part of the process to create post-mining landforms that are stable, sustainable, and suitable for the PMLU. Landform design can help to prevent erosion, improve water quality, and promote the growth of vegetation on mine rehabilitation areas (Hancock et al., 2020).

There are a number of factors that need to be considered when designing landforms for mine rehabilitation, including the type of mining activity, the climate, the soil, the spoil, the surrounding landscape, water drainage and the PMLU (Howard et al., 2011; Australian Government, 2016b). These should be characterised prior to mining by surveying, surface and groundwater modelling and material characterisation (Howard et al., 2011). Careful landform design will improve erosion control and plant growth, contributing to the success of the rehabilitation (Howard et al., 2011; Howard, 2018). Computational tools used to carry out landform design create 3D models of the landscape and simulate the effects of different design options (Howard et al., 2011). Designs for grazing land should incorporate appropriate slope, drainage, rockiness or surface roughness, and soil properties (Short, 2023). Landform designs may allow for subsequent landform evolution modelling to predict rates of erosion and plan for maintenance (Hancock and Willgoose, 2021) and have been calibrated for pasturelands, although these calibrations did not account for any potential erosion related to different grazing regimes (Hancock et al., 2021). Nonetheless, landform design and evolution modelling may provide evidence during the planning stages that the land is expected to be safe and stable.

3.2.2 Land Suitability Assessment

The Queensland Government’s Land Suitability Assessment is a process that evaluates the potential of land at the paddock or parcel scale for a specific land use, i.e., cattle grazing or sugar cane cropping. Land Suitability Assessment assesses physicochemical characteristics and is therefore particularly suited to an early stage in the rehabilitation, i.e., prior to seeding, when it can be used to show that the rehabilitation area is suitable for pasture vegetation and subsequent grazing by livestock.

Land Suitability Assessment considers a range of "limitations", including:

- water availability
- nutrient deficiency
- nutrient availability and toxicity
- surface condition
- salinity
- rockiness
- slope
- microrelief
- water erosion
- subsoil erosion.

For a full list of limitations please see, (DSITI and DNRM, 2015), and for the subset of limitations considered relevant for mine rehabilitation in the Bowen Basin please see Short (2023).

Measured levels of these limitations will define whether the land achieves the following classes:

- 1: suitable land with negligible limitations
- 2: suitable land with minor limitations
- 3: suitable land with moderate limitations
- 4: unsuitable land with severe limitations
- 5: unsuitable land with extreme limitations.

Considerable work has been carried out to map levels of these limitations to the above classes for mined land, and is presented in Short (2023). For more information on the Land Suitability Assessment guidelines and regional frameworks please see DSITI and DNRM (2015) and DNRM and DSITIA (2013), respectively.

3.2.3 Land Capability

The Queensland Government's Land Capability assessment is a process that evaluates the potential of broad scale land areas for broadly defined land uses, such as cropping, pastoral, or non-agricultural. It considers a range of factors, including soil type, slope, and climate. Land Capability is less specific than Land Suitability Assessment and has eight classes spanning capacity for cultivation and grazing. These classes are:

- I: land suitable for all agricultural and pastoral uses
- II: land suitable for all agricultural uses but with slight restrictions for cultivation
- III: land suitable for all agricultural uses but with moderate restrictions for cultivation
- IV: land primarily suited to pastoral use, but which may be safely used for occasional cultivation with careful management
- V: land that in all other characteristics would be arable but has limitations that make cultivation impractical and/or uneconomic
- VI: land that is not suitable for cultivation but is well suited to pastoral use
- VII: land that is not suitable for cultivation but on which pastoral use is possible only with careful management
- VIII: land that has such severe limitations that it is unsuited for either cultivation or grazing (DSITI and DNRM, 2015).

Land Capability classes I-VII are suitable for grazing. Assessment of Land Capability is performed using the same list of limitations as that employed for Land Suitability assessments, the difference being that the land uses are predefined (DSITI and DNRM, 2015). Diagnostic attributes for these limitations are outlined in Table 8 of the Guidelines for Agricultural Land Evaluation in Queensland (DSITI and DNRM, 2015).

In the 1995 Technical Guidelines for the environmental management of exploration and mining in Queensland, it is noted that Land Suitability Assessment is recommended over Land Capability assessment for use in the mining industry. This is because the Land Suitability Assessment criteria are targeted towards particular land uses at a more refined scale, whereas Land Capability is recommended for use in broadscale or reconnaissance assessments (Queensland Department of Minerals and Energy, 1995 and DSITIand DNRM, 2015). Land Suitability Assessment rather than Land Capability assessment may therefore provide the more appropriate criteria for proponents to work towards, particularly for the earlier milestones associated with development of the final landform and soils.

3.2.4 Agricultural land classification

Agricultural land classification is a system that classifies land according to its suitability for agricultural production based on a number of factors, including soil type, climate and drainage. Assessed land is classified into four main classes:

- Class A: crop land
- Class B: limited crop land
- Class C: pasture land
- Class D: non-agricultural land.

Within Class C, C1 is attributed to high fertility grazing land suited to cattle fattening, C2 is suited to sheep and cattle breeding, and C3 suitable for low stocking rates. Agricultural land classification is based upon Land Suitability Assessment and/or Land Capability data for a particular area. Classes C3 and above (towards A1) are suitable for grazing.

Although there are various tools which could be applied to demonstrate that rehabilitated grazing land is safe, stable and non-polluting, previous work from the OQMRC has adapted the Land Suitability Assessment to mined land in the Bowen Basin (Short, 2023) and also highlighted the importance of landform design to plan for a safe, stable rehabilitation area (Short and Bourne, 2023).

3.3 Demonstrating rehabilitation which sustains a grazing post-mining land use

Monitoring provides a foundation for assessing the progress and condition of the rehabilitation of mined areas and is important in rehabilitating mined land to a grazing PMLU. Monitoring programs in PRC plans outline the methods and frequency of monitoring (Department of Environment and Science, 2021). The broad objectives of monitoring programs are to demonstrate that the land continues to be safe, stable and non-polluting, and is also able to sustain the PMLU.

Objectives set out in robust monitoring plans will follow SMART principles, align with milestones, and be assessed by well-defined methods (Department of Environment and Science, 2021). For example, if quantitative goals assessed by a robust and specific method (e.g., “70% groundcover as per VegMachine method at the end of the dry season”) are not outlined during planning, it may be difficult to benchmark the progress of the rehabilitation. Additionally, high quality monitoring using scientifically and statistically defensible tools that are accepted by agriculture and government may be considered a leading practice. Such monitoring will allow risks and opportunities to be identified early and managed adaptively (Australian Government, 2016a). Despite these potential benefits, the most appropriate tools for measuring rehabilitation monitoring goals has not been discussed in the mine rehabilitation literature, to our knowledge.

Various monitoring tools have been developed for Queensland pasturelands and are described and compared here, and further in Appendix Table 3. These tools include LCAT, Stocktake, VegMachine and LFA. These tools require comparison as they are built with different intents, parameters and limitations. For example, some are designed to monitor productivity (i.e., Stocktake), whereas others are designed to monitor landscape function (i.e., LFA), or overall land condition (i.e., LCAT) and therefore particular tools may be more suited to implementation in different mine rehabilitation scenarios than others.

Furthermore, some tools assess land relative to analogue sites or regional benchmarks (e.g., VegMachine or LFA) while others have built in benchmarks (e.g., Stocktake and LCAT), leading to different considerations at the planning stage (i.e., location of an analogue site vs. designation of a benchmark). It is of note that selection of an inappropriate analogue site may lead to soft or unachievable targets for the PMLU (see Section 2.3). Using tools with inbuilt benchmarks may circumvent these issues.

3.3.1 Land Condition Assessment Tool (LCAT)

LCAT records information for a considerable suite of variables, including important measurements of erosion and pasture composition (Hassett, 2021). Data input for LCAT is through an ESRI 123 survey in which assessors select from pictograms representing values associated with a set of indicators of long-term land condition. The tool's use of pictograms representing science-based indicators and concepts broadens its accessibility and makes it efficient in the field. It is of note that some plant identification skills are advantageous in completing the survey.

LCAT outputs 15 results, including condition and land management guidance and hazard identification. Land management guidance may inform adaptive management, which is considered a useful practice to achieve the desired PMLU (Lamb et al., 2015). LCAT also reports on certain hazards related to resilience, with warnings displayed for fire, landscape stability, erosion, water quality, and invasive pest risks, allowing for adaptive management of those risks to encourage the resilience of the land. Importantly, LCAT allows for the capture and private storage of relevant land resource and contextual data within the platform for analysis and monitoring.

3.3.2 Stocktake

Stocktake is a simple monitoring method which can be used to determine land condition and productivity. The tool requires minimal data input, although some plant identification skills are necessary, such as knowledge of unpalatable species. Stocktake measures pasture, soil, woodland and forage condition to develop a grazing land condition score, i.e., an ABCD ranking, which is an indicator of carrying capacity (Queensland Department of Primary Industries and Fisheries, 2004). Stocktake measures comparatively few parameters and is focussed on productivity: it may therefore overlook important parameters for rehabilitated lands. For example, while it considers "weeds", this assessment does not record the weeds' identity and therefore their identification is highly subjective. In light of its lack of invasive plant monitoring, alongside its limited capacity to assess fire risk, it may not be sufficient to demonstrate that the rehabilitation is safe, stable and can sustain a PMLU. However, it does output a carrying capacity report, which if replicated year on year could be used to show that grazing can be sustained over time.

3.3.3 Landscape Function Analysis

LFA is a tool which assesses the effectiveness of the land as a biophysical system which either leaks or gains function. This perspective is of interest for progressive rehabilitation as it may allow for rehabilitation practitioners to assess the progress of their rehabilitation efforts and prove that the land is stable, and self-sustaining, and therefore whether adaptive management, such as soil amendments, is required. However, if the land is being monitored frequently via LCAT and/or Stocktake and is progressing towards an "A" condition in the reports generated by either tool, it may be deduced that the landscape is also gaining function and is self-sustaining. LFA, in comparison to LCAT, does not assess pasture composition, and therefore pest vegetation may go unchecked, which poses risks for the landscape. For example, Buffel grass may dominate in a rehabilitation area, become moribund and present a fire risk; or invasive flora may spread from the rehabilitation area, threatening native flora. In essence, if the land presents a hazard as a bushfire risk or source of invasive flora, it may not be flagged by LFA and lead to poor environmental outcomes.

3.3.4 VegMachine

VegMachine is a tool which uses remote sensing to generate reports regarding groundcover of Australian rangelands. It assesses brown and green groundcover of a certain area over various seasons, and meshes this data with rainfall data (Beutel et al., 2019). From this, the tool predicts an estimate of annual soil erosion and foliage (Beutel et al., 2019). Remote sensing means that the area of interest can easily be compared to other areas in the region, simplifying comparison to analogues. This method is less burdensome on rehabilitation practitioners, and monitoring can be performed remotely, with more data points than conventional field-based tools. Additionally, the whole rehabilitation area can be surveyed, instead of using line transects or quadrats, providing a complete picture. However, it is limited in its outputs, as it does not comprise soil and weed sampling, and therefore may overlook certain threats to the pasture. It is therefore unlikely to be able to show that the pasture can sustain grazing as its main outputs are related to pasture productivity and groundcover. Nonetheless, these parameters are important facets of successful rehabilitation to grazing. Also of note is that the VegMachine platform can be used to produce FORAGE reports. FORAGE is discussed further in Section 3.3.5.

3.3.5 Modelling to demonstrate that land achieves stable and sustainable grazing

Monitoring of land, pasture and livestock condition can be used to determine that the land has reached a stable condition that currently supports the PMLU but it does not demonstrate sustainability of the use into the future. To predict the sustainability of a grazing PMLU, carrying capacity and pasture modelling tools may be implemented. To run these models, monitoring data (which may be gathered using the methods discussed above) is used as input. This provides an opportunity to select methods which will gather complementary monitoring data for input into models, allowing proponents to demonstrate that a self-sustaining pasture has been created.

Available models include the FORAGE long-term carrying capacity (LTCC), SWIFTSYND, GRASP and AussieGRASS models (Appendix Table 4). These models predict the appropriate stocking rate of the land and/or pasture growth rate and may be used to determine likely outcomes of management strategies across multiple years. Other outputs include predicted runoff (SWIFTSYND, GRASP and AussieGRASS) and nitrogen dilution (GRASP). AussieGRASS and SWIFTSYND are both derived from GRASP modelling.

None of the models presented here take into account future climate scenarios, which are expected to significantly affect stocking rates and forage production (Godde et al., 2019). However, SWIFTSYND, GRASP modelling, and AussieGRASS do allow for users to input their own climate files, which could allow for prediction of carrying capacity under different climate scenarios. Although this may be a suitable approach, the literature surveyed did not trial this method, and it may therefore be considered as experimental. In a future version, FORAGE LTCC is expected to “enable assessment of climate change impacts on LTCC”, which will be useful for providing more accurate reports (Zhang et al., 2021).

Historically, grazing trials have been used to demonstrate the stability of the land under grazing pressure. Grazing trials are valuable as far as they allow for a practical pilot, which may demonstrate the ability of the land to support livestock. However, they have certain limitations, such as the fact that trials are not often run for amounts of time which indicate “sustainable” grazing over multiple seasons, and that trials may not encompass “bad” seasons. Such oversights may cause the overestimation of the carrying capacity of the land or for the results of grazing trials to be extrapolated to other rehabilitation areas which may not have similar pasture quality and quantity (Sollenberger and Burns, 2001). Results from these grazing trials could erroneously describe the land as able to sustain a grazing use and could lead to unsustainable management practices.

Pasture modelling, on the other hand, takes the land condition, climate, and (sometimes) management methodologies and can determine pasture growth and appropriate stocking rates. Pasture modelling can give indicators of uncertainty and assist in planning for sustainable grazing and management practices which prevent degradation of the land (Clewett et al., 2021). As with all modelling investigations, good quality input data which is derived from monitoring and used to parameterise the model will increase the reliability of model outputs.

3.3.6 Land management

To maintain the land in an acceptable condition until and beyond certification, the land should be managed appropriately. Surrendered rehabilitated grazing land will also require ongoing management. To improve their acceptance, these management considerations should be planned for by the proponent and communicated with the subsequent landholder and/or relevant grazier early and often, or even be developed collaboratively with the grazier (Maczkowiack, 2009). Management of rehabilitated grazing land is likely to differ from management of adjacent unmined grazing land as it may be more susceptible to erosion than unmined land when heavily grazed (Grigg et al., 2002). This may mean that stocking rates will have to be lower than adjacent unmined land stocking rates. Furthermore, to ensure that groundcover is above a certain threshold, e.g., 70% (Grigg et al., 2001), proponents will have to communicate that special consideration will have to be given to the aridity and the soil fertility of the rehabilitated land. Aridity has been shown to limit the land, with arid climates leading to lower safe utilisation rates (Clewett et al., 2021). While aridity is also a consideration for adjacent unmined lands, the risks to landform stability may be riskier for mined rehabilitated areas. Furthermore, soil fertility may be lower on rehabilitated areas than unmined areas due to the use of spoil within growth media and the limited amount of topsoil available at many mine sites. Consequently, rehabilitated land may require management which considers this lower soil fertility, as the safe utilisation rates of lands with lower fertility soils will be lower than those with higher fertility soils (Clewett et al., 2021).

In order to manage the land appropriately, management should not be fixed: adaptive management can be used to identify and quantify risks, and correctively alter management practices (Queensland Department of Environment and Science, 2021). To assist in the adaptive management and decisions pertaining to stocking rates, Clewett et al. (2021) recommends the use of a pasture modelling tool such as GRASP or FORAGE LTCC. It may also be of use for graziers to continue to monitor the land with one of the monitoring tools discussed above, such as LCAT. LCAT offers an additional advantage as it provides adaptive management advice and warnings related to fire and erosion which may promote the sustainability of the PMLU after the land is surrendered. Further discussion of grazing management on rehabilitated land include Grigg et al. (2000) and Short and Bourne (2023).

Furthermore, tools and practices to sustainably manage a rehabilitated pasture may include:

- weed and pest control (Tracy et al., 2018; Hassett et al., 2021; Short and Bourne, 2023)
- controlled burns (Short and Bourne, 2023)
- water management (Silcock and Hall, 2014; Short and Bourne, 2023)
- erosion control (Grigg et al., 2000; Short and Bourne, 2023).

Some facets of these practices may be rehabilitation specific, and some are similar to management of conventional Queensland grazing lands. For an extensive discussion of rehabilitation specific management, see Short and Bourne (2023), Australian Government (2016), and Trevaskis and Trotter (2022). For conventional grazing management refer to Hunt et al. (2014) and the resources at https://www.longpaddock.qld.gov.au/ and https://www.mla.com.au/. As previously mentioned, management practices should be complemented by appropriate monitoring, which may include the above tools but may also include water sampling if appropriate (please refer to ANZECC & ARMCANZ, 2000 for the appropriate trigger values). We also acknowledge that carbon sequestration and credit generation methods present management opportunities for proponents (Trevaskis and Trotter, 2022) and require further investigation.

4 Discussion

4.1 Objectives of rehabilitation to grazing in Queensland

The review presented here highlights that there are various objectives when it comes to rehabilitation to grazing in the international and national literature, such as conservation grazing (Etter, 1973; The Mining Association of Canada, 2021), grazing as a natural resource management tool (Petra Diamond Mines, 2022), and commercial grazing (Trevaskis and Trotter, 2022). In Queensland, the literature highlighted that most research had focussed on demonstrating that rehabilitated land was capable of an intended final use of commercial grazing (Bennett et al., 2021; Paton et al., 2021). In some cases, including within Queensland, rehabilitation to grazing aimed to align with community aspirations (Glencore, 2023a), which we assume in this region may involve use of the land as part of a commercial cattle enterprise due to the lack of alternative grazing types explored in the Queensland-based literature.

Due to the range of objectives for grazing lands, in the same way that PMLUs are selected, it may be helpful to determine the type of grazing enterprise via a suite of tools in order to set clear objectives and milestones. This approach aligns with the guidance in Queensland which outlines that the rehabilitation plan should include an “evidence based comparison and justification for each proposed PMLU against alternative options” (p.21, Department of Environment and Science, 2023). Tools to compare options include options analysis, multi-criteria selection, the five capitals framework, Land Suitability Assessment of the pre-mining landscape, and community consultation (Department of Environment and Science, 2021; Côte et al., 2023). These tools may be employed during the planning phase of a project.

If commercial vs. another type of grazing is intended (such as low-intensity grazing which is potentially not commercially viable), then proponents may wish to consult community on these distinctions to avoid improper use of the land post-surrender, a risk that was exemplified in Rugadya (2020).

Clear definition of objectives for a grazing PMLU (e.g., conservation grazing vs. commercial cattle breeding enterprise vs. commercial sheep grazing) will ensure specific SMART criteria are developed which align with the end use. For example, commercial sheep grazing may require a different level of pasture productivity and different water quality than commercial cattle grazing, and therefore milestones may be defined accordingly during the planning phase. Additionally, management of the land should align with the objectives all while considering the limitations of the rehabilitation. For example, groundcover of a rehabilitation area may need to be at 70% to reduce erosional processes, and monitoring and adaptive management of the land should be carried out accordingly (Grigg et al., 2001). In summary, in order to demonstrate success of rehabilitation to grazing, the specific objectives of the grazing must be identified and appropriately planned for.

4.2 Safety and stability of the landform – a need for extensive *in situ* trials

Studies of erosional stability and safety of the rehabilitated grazing landform were found within the literature and underscored that grazing could jeopardise the stability of the landform (Grigg et al., 2002). However, these did not involve grazing trials and were limited by their duration, and therefore did not reflect real world conditions over long time scales. Furthermore, landform evolution modelling has been calibrated for pasturelands but was only subjected to light intensity grazing during calibration trials (Hancock et al., 2021). Long term grazing trials which measured soil loss, water quality, pasture condition and animal production have been performed on unmined land, spanning 17 years (State of Queensland, 2015). These trials highlight practices which may inform future grazing trials, including the length of trials, inclusion of a variety of seasons (including drought), number of replicates, and variety of variables measured. This variety of variables included:

- animal production—weight gains, carcass values etc.
- pasture condition and production, plant demography
- soil loss and water quality
- biodiversity—fauna and flora
- soil carbon and sequestration
- fire effects on trees and shrubs (State of Queensland, 2015).

These measurements may be complemented by collection of data relating to soil quality and depth, root penetration, and carcass organ toxicity as per the information presented throughout this report and in Appendix Table 1. Collecting such a variety of measurements over an extended period during a grazing trial is likely to generate a holistic picture of how rehabilitated land will respond to different grazing regimes over time. This knowledge would allow proponents to establish grazing types conducive to the achievement of a safe, stable and non-polluting landform which could sustain grazing. Furthermore, toxicology measurements may be useful to determine if there are any contamination risks to the meat and may be integrated into grazing trials. All in all, more extensive grazing trials and calibration of landform evolution models under a variety of climatic and usage regimes may benefit the planning and management of areas of land which are rehabilitated to grazing. This may be useful for initial and subsequent land managers of those areas and help achieve a stable outcome.

4.3 Tools for demonstrating a safe, stable, and non-polluting landform which can sustain grazing

Various tools were identified to determine if rehabilitated mined land is safe, stable, non-polluting and could sustain a grazing PMLU. As per Short (2023), using the Land Suitability Assessment framework to plan, construct and assess rehabilitated grazing land will assist in demonstrating that the land is likely to be safe, stable and non-polluting. This may also be accompanied by a contaminated land assessment and materials characterisation to test whether the land will not be toxic to users or the surrounding environment. In addition to this, once the pasture has been established, monitoring and modelling may be used to demonstrate that the land is able to sustain a grazing PMLU. For example, if the objective is that the rehabilitation will support a particular intensity of cattle grazing, then monitoring and modelling should show that the pasture yields are sufficient for that use and are predicted to remain so in a variety of seasons. Additionally, monitoring tools such as LCAT may also be able to assess the resilience of the pasture, which could build confidence in the sustainability of the PMLU. These tools may be built into a monitoring programme which would further build confidence in PMLU sustainability. Consequently, leading practice likely involves a robust monitoring plan with scientifically defensible tools. These tools would monitor a variety of facets of the rehabilitation and be appropriate for the goals of the rehabilitation (i.e., high intensity animal production vs. conservation grazing). Tools for monitoring and modelling should be used iteratively alongside management measures until proponents can robustly demonstrate that the rehabilitated land is safe, stable, non-polluting and can sustain the grazing PMLU. Rehabilitation to grazing generally follows a sequence of milestones that involves PMLU selection, landform shaping, topsoil application and seeding, monitoring to demonstrate that the land is stable and modelling to demonstrate that the land can sustain the grazing PMLU. Tools described here and in (Short 2023; Short and Bourne, 2023) may support the different steps in this process.

5 Conclusion

In conclusion, our review of international, national, and Queensland-specific literature on grazing as a PMLU has elucidated key issues relating to the objectives, landform safety and demonstration of successful rehabilitation outcomes. This literature review unearthed a diverse range of objectives for grazing rehabilitation, encompassing conservation practices, land management strategies, and commercial pursuits, with much of the Queensland-based research focussing on pasture productivity and livestock weight gain. Additionally, studies delved into critical factors such as landform stability, erosion control, and the impact of contamination on grazing animals, providing valuable insights into the complexities of this use.

Resilience emerged as an important topic of discussion, prompting deliberation on whether it should be considered a prerequisite for demonstrating sustainability in grazing rehabilitation. We also found that while final milestone criteria were proposed in the literature, they have yet to find widespread adoption among proponents.

Within the Queensland context, we identified tools that could effectively demonstrate that rehabilitated land is safe, stable, and non-polluting, making it suitable for a grazing PMLU. Our exploration encompassed crucial tools like landform design, Land Suitability Assessment, Land Capability evaluation, and agricultural land classification. Furthermore, we highlighted prior work that adapted the Land Suitability Assessment to the unique conditions of rehabilitated mined land in the Bowen Basin, establishing a foundation for future rehabilitation planning.

In terms of monitoring to demonstrate that rehabilitated land can sustain a grazing PMLU, we scrutinised an array of tools including the Land Condition Assessment Tool (LCAT), Stocktake, Landscape Function Analysis (LFA), and VegMachine. Modelling approaches to demonstrate the same aim and which would accompany monitoring may include GRASP, FORAGE LTCC, AussieGRASS, and SWIFTSYND. Our discussion elucidated the distinct advantages and limitations of each tool within the specific context of mined land rehabilitation for grazing.

Our review uncovered critical knowledge gaps. One noteworthy knowledge gap was the lack of clear objectives for grazing land use in Queensland, possibly the result of a failure to clearly define the type of grazing enterprise to be achieved by the PMLU. Although the literature highlighted that the main focus of research was productivity, the feasibility of grazing operations on mined land was unclear, especially with regards to the resultant limitations and constraints associated with rehabilitation grazing land. Furthermore, a notable deficiency in mid-to-long-term grazing trials (> 5 years) addressing the stability of rehabilitated landforms was identified. The uncertainties surrounding the best practices for demonstrating successful rehabilitation for grazing may be mitigated somewhat by the judicious and stringent application of the decision making, assessment, monitoring and modelling tools presented in this document.

Given the prevalence of grazing as a PMLU in Queensland, this report highlights the importance of performing comprehensive long term grazing trials on previously mined land and demonstrating landform stability under grazing pressure.

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7 Appendix

Appendix Table 1. International, interstate and Queensland-based academic and grey literature of grazing on rehabilitated lands

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Canada	Conservation grazing of wood bison	Not research	Not research	(The Mining Association of Canada, 2021)	"Syncrude approached Elk Island National Park to participate in the Wood Bison Recovery Program, run by the Canadian Wildlife Service, and in 1993, 30 wood bison were released onto reclaimed land. 25 years later, the herd has now grown to 300, who graze on 300 hectares of land reclaimed from oil sands mining operations at the Beaver Creek Bison Ranch, which is managed in partnership with the Fort McKay First Nation"
Canada	Winter range (bighorn sheep) – conservation grazing	Establishing appropriate seed mixes for revegetation of disturbed land	Hydroseeding trials	(Etter, 1973)	This paper develops a suggested list of revegetation species for seeding reclaimed winter rangelands for bighorn sheep.
South Africa	Cattle grazing including grazing as a natural resource management tool	Not research	Not research	(Petra Diamond Mines, 2022)	The Finsch mine "was seeded in two South African biomes: Savannah and Nama-Karoo. The paddocks as a rehabilitated area are earmarked as grazing land post mine closure. The end of the project also included putting up fencing and laying infrastructure for fresh water. Although well grown, the area was not blending into the surrounding environment and the dominant grass species were more suitable for higher rainfall areas. To address this, a decision was taken to graze the area as the added movement of cattle would loosen up compacted ground allowing better seed germination for the next season as well as providing organic fertiliser."
Australia	Cattle grazing	Not research	Not research	(Glencore, 2023a)	Update on Glencore's rehabilitation across mine sites in Australia. Includes description of areas certified for grazing.

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia, (Bowen Basin Queensland)	Cattle grazing	Development of a potential silvopastoral model for sustainable grazing on mined land	Surveys and literature review	(Trevaskis and Trotter, 2022)	Development of a potential silvopastoral model. Surveys of completion criteria (final milestone criteria). Surveys of grazier plans for surrendered land and mine adjacent land.
USA (Eastern)	Cattle grazing and other PMLUs	Literature review	Review	(Zipper and Skousen, 2021)	Mined-land hay lands and pastures are used for grazing livestock. They are created by revegetating mined land with grasses and legumes. The land must be suitable for grazing, which means it must have the right soil, slope, and water. The rehabilitation process begins by clearing any woody vegetation. Then, the land is seeded with grasses and legumes. If the land is not suitable for grazing, it may need to be fertilized or treated for invasive plants. Mined-land hay lands and pastures can be a cost-effective way to graze livestock. However, they may require more management than natural pastures.
USA (North Dakota)	Cattle grazing	Determine pasture yields, seasonal balance (of grasses) and diversity during grazing on different ages of reclaimed lands	Grazing trial	(Trosen et al., 2003)	Grazing can be started on reclaimed grasslands 2- to 4-years after they are seeded. A study of 2- to 4-year old re-established grasslands found that grazing can improve the balance of cool-season and warm-season grasses. Grazing in the early season reduced the cover of cool-season grasses and increased the cover of warm-season grasses. This resulted in a more balanced plant community.

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia, Hunter Valley (NSW)	Cattle grazing	Show sustainability and economic feasibility of grazing	Grazing trial with comparison of mined vs unmined analogue sites. Soil and plant testing for heavy metal toxicities, pH, and nutrients. Pasture diversity and coverage monitored. Cattle heavy metal deficiency or toxicity. Live weight gain and condition of steers was measured.	(Griffiths and Rose, 2017)	Soil testing identified no heavy metal toxicities and broadly adequate nutrients and pH. Plant analysis revealed no heavy metal toxicities. Pasture monitoring showed good diversity with certain dominant sown species. Ground cover and weeds remained constant under the grazing trials. Animals showed no heavy metal toxicity. Steer weight and condition was better on rehabilitated vs. analogue sites. The project also outlines management options to improve outcomes for rehabilitation to grazing.
South Africa	Cattle grazing	Measure paddock vegetation biodiversity with and without grazing	Grazing trials including an exclusion trial	(Thovhakale, 2010)	No significant biodiversity changes could be observed by excluding cattle from the rehabilitation, but this is potentially due to the short term nature of the grazing trials.
USA (Appalachia)	Cattle grazing	Cow-calf production on reclaimed pastures: pregnancy and calf weights	Grazing trial	(Teutsch et al., 2008)	Because of productivity limitations, grazing systems established on mine soils created from rock spoils sustain lower animal densities than would be typical on natural soils.

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia (Acland, Queensland)	Cattle grazing	Sustainability and feasibility trials	Grazing trials and GRASP modelling	(Clewett et al., 2021)	Rehabilitated lands have higher pasture growth than unmined lands, which leads to higher beef production and economic returns. Grazing pressures up to 30% utilisation of annual pasture growth are sustainable for beef production on rehabilitated lands. "The LTCC for the rehab paddocks (36–59 AE/100 ha) is similar to stocking rates used in the New South Wales Hunter valley region of 38 head/100 ha for rehab pastures of Rhodes grass, panic and kikuyu (Griffiths and Rose 2017), but marginally higher than LTCC estimated for Buffel grass rehab pastures of 17–45 AE/100ha in central Queensland (Grigg et al., 2002)."
Australia (Bowen Basin, Queensland)	Cattle grazing	Model erosion, predict safe stocking rates, determine management practices, quantify vegetation cover, forage, and pasture compositions under different grazing scenarios	Grazing trials	(Grigg et al., 2002)	Predicted sustainable stocking rates at sites on Blackwater and Norwich Park mines were 2.7 and 2.2 ha/head, respectively. A minimum of 70% groundcover to be maintained on mine rehabilitation grazing. They also observed that cattle affect the amount of vegetation cover and directly impact soil erodibility through hoof action, which causes degradation in soil structure, resulting in reduced infiltration and therefore increased runoff; and a 'loosening' of the soil surface which promotes entrainment in overland flow. They discovered site specific grazing pressure thresholds above which erosion was exponential.
Australia (Queensland, New Acland)	Cattle grazing	Understand differences in soil properties between mined rehabilitated and unmined grazing lands	Grazing trials: root penetration, soil properties	(Melland et al., 2014)	Preliminary results suggest little difference between the rehabilitated and control sites, with the exception of higher plant-available P in two rehabilitated sites, in terms of benefits or constraints to pasture production.

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia	Not stated explicitly throughout, mentions cattle.	Synthesise literature pertaining to stakeholder engagement for PMLU decision making	Literature review	(Everingham et al., 2018)	This paper proposes a framework for engaging “a stakeholder panel in planning post-mining land uses in Australia” in order to achieve a beneficial use for the land. I “identifies a potential role for stakeholders in adaptive management in collaboration with regulators and mining companies”.
Australia – Queensland (Bowen Basin)	Beef cattle grazing	“Identify and evaluate models for stakeholder involvement in post-mining land use change issues in the Bowen Basin”	Workshop discussions	(Rolfe et al., 2018)	“Outcomes of the workshop discussions about factors relevant to post mining land use were: • Stakeholder engagement was viewed as important for planning end-of-mine land use change, • Grazing was viewed by stakeholders as a viable land use on post-mining lands. • Landholders will accept ‘packages’ of land that have a mix of productive and non-productive country types, and do not require every hectare of the property to be productive. • There was some support for some mining lands to be returned to native vegetation, but only as part of grazing properties. • Options for making post-mining land suitable for grazing enterprises would need to be negotiated on a case by case basis, • Ideally the planning and engagement would not be last-minute and the end-use landholder would be determined before mine closure, perhaps with the transition involving a lease arrangement followed by eventual purchase. • There was some more limited interest in other options for land use, such as biofuels or farm”

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Uganda	Cattle grazing	Describe case studies of land conflict in post-mining economies	Case studies and expert consultation	(Rugadya, 2020)	Customary land tenure in Ugandan mining areas often has communal grazing right. After mining, it is unclear when these rights are to be resumed (if at all). “Neither the companies nor the government (department of geological surveys and mines) is disclosing post-mining management plans to communities, which are submitted during the process of applying for licenses.” “communities are not aware (of plans), the only wakeup call is grazing animals falling in deep pits and getting trapped or breaking limbs”
Australia, Queensland	PMLUs including cattle grazing	Not research	Not research	(Queensland Resources Council, no date)	Case studies of rehabilitation across the state including examples of certification to grazing.
Australia, Queensland, Dawson Mine	Cattle grazing (weaners) – including discussion of weight gain	Not research	Not research	(Metallurgical Coal Limited, 2019)	Description of rehabilitation outcomes at the Dawson Mine.
Australia, New South Wales	Cattle	Not research	Not research	(Glencore, 2023b)	Brief website publication announcing that a grazing trial had been performed.
Australia, Queensland	Cattle grazing	Literature review and expert opinion	Which biophysical conditions are the pre-requisites for rehabilitating land to safe, stable and non-polluting land which can sustain a grazing PMLU?	(Short, 2023)	Document uses Land Suitability Assessment to define leading practice for rehabilitated grazing lands in Queensland

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia (Bowen Basin, Queensland)	Cattle grazing	Model erosion, predict safe stocking rates, determine management practices, quantify vegetation cover, forage, and pasture compositions under different grazing scenarios	Extension of grazing trials in Grigg et al. (2002)	(Grigg et al., 2006)	The authors showed that stocking rates should be site specific. They also found that factors influencing the ability of the pasture to trap and store moisture were the key to pasture productivity.
Australia, Queensland, Toowoomba region	Cattle grazing	“Assess the potential for soil that was previously farmed, then mined and rehabilitated to support pasture for commercial cattle production”	Examination of soil and spoil characteristics on rehabilitated grazed land, with unmined land as a control site	(Bennett et al., 2021)	“It was concluded that: 1) abiotic properties of rehabilitated soils fell within the range of un- mined soils; 2) viable pasture production was achieved from the rehabilitated sites; and 3) both the replaced soil layer and the mine spoil supported root exploration and pasture production”
Australia, Queensland, Bowen Basin	Cattle grazing	The research aims to “develop an approach for assessing end-use risks for the region’s mined land, and develops risk assessment models for selected end-uses”	Web based survey to identify risks of grazing rehabilitated land, then conceptual risk models were developed.	(Maczkowiack and Smith, 2012)	The risks identified by the survey were “surface erosion, sub-surface erosion, bushfires, weeds and feral animals”. Adaptive management may improve modelling for risk.

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia (Bowen Basin, Queensland)	Cattle grazing	Assessment of risks of grazing mined lands	Risk assessment	(Maczkowiack, 2009)	Grazier attitudes are pivotal to managing risks associated with grazing. Overgrazing is a real possibility of rehabilitated lands, jeopardising the sustainability of the land.
Jamaica	Cattle grazing	Not research	Not research	(Bounds, 1974)	History of bauxite mining in Jamaica and its restoration.
Ireland	General grazing	Determine whether grass and soil is likely to impact grazing animals	Soil and grass samples	(Aslibekian and Moles, 2003)	A risk assessment of contamination from abandoned mines was conducted in a district. The assessment found that extensive areas of soil were contaminated with cadmium (Cd), lead (Pb), and zinc (Zn). The most affected areas were floodplains located 2–3 km downstream from the site. The assessment also found that Pb posed the greatest risk to grazing animals due to its high toxicity and high concentrations in soil. Within floodplain areas, grazing cattle may intake a lethal dose of Pb.
Canada	Cattle grazing	Determine impact of molybdenum in soils on cattle health and residual levels in meat	Grazing trial and necropsy	(Steinke and Majak, 2003)	Cattle subjected to forage with a high concentration of molybdenum from one of the reclaimed mine sites showed signs of molybdenum poisoning. Although this article focuses on animal welfare and condition, there may be implications for the sale of the meat as it contains some residues of this element.
Australia, Queensland	Cattle grazing	What are the risks to meat of grazing cattle on rehabilitated tailings with regards to heavy metal uptake?	Grazing trials on rehabilitated tailings facilities. Feeding trials with fodder spiked with tailings. Blood, biopsy and necropsy materials were collected. Arsenic, lead and other metals were measured.	(Ng et al., 2014)	Calculation of a predictive model for maximum beneficial use of rehabilitated tailings for cattle grazing (i.e., how long you can graze cattle of tailings without having negative toxicological outcomes for the cattle/meat).

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia, (Bowen Basin, Queensland)	Cattle grazing	Develop completion criteria for grazing rehabilitation	Review of collated data and literature	(Grigg et al., 2001)	• Achieve and maintain vegetation cover of at least 70% • Regrade slopes to less than 12% • Media properties reducing infiltration affect the influence of vegetation and slope • Reduce rootzone salinities to less than 0.6 dS/m (on 1:5 basis) • Media properties influence salinity reduction over time A minimum CEC of 8-10 is required for adequate nutrient retention.
USA	Meadow, hay, grazing, and grazing-feeding.	Evaluation of carbon and nitrogen stocks and related soil physical and chemical properties for reclaimed grassland sites under four management practices: meadow, hay, grazing, and grazing-feeding.	Soil analysis	(Ussiri et al., 2006)	Bulk density of the reclaimed mine soils (RMS) was significantly lower for the hay and meadow than the grazed sites. RMS under hay and meadow practices had greater concentration of water-stable aggregates (WSA) and larger mean weight diameter (MWD) of aggregates than the grazed sites. Soil pH and electrical conductivity (EC) were higher in the RMS than the undisturbed soils. Among the reclaimed sites, pH and EC values were generally lower ($P < 0.05$) in meadow than grazing and grazing-feeding practices. The soil organic carbon (SOC) was generally higher in the grazing-feeding and hay sites than meadow, grazing, and undisturbed grassland. Nearly 50% of the root biomass accumulated in the top 0-10 cm in the reclaimed grassland sites. The SOC content was strongly correlated with MWD and root biomass, indicating that both roots and aggregates play a significant role in SOC accumulation in RMS.

Country/region	Grazing type	Aim of research	Method	Citation	Main findings and/or key information
Australia, Hunter Valley (NSW)	Cattle grazing	Review past and present mine rehab work. Determine timeframes for establishment of pasture. Gap analysis for future research.	Review of monitoring data from 107 rehabilitation to pasture sites and 15 natural pasture analogue sites. Field assessments of pastures and soils at 20 successful rehab sites.	(Cox et al., 2021)	Report highlights paucity and limitations of available data. Variability in how long it took for the pastures to establish sustainably – up to 12 years based on soil organic carbon requirements Future research priorities included: 1) completion criteria, 2) evaluation of management practices, 3) analogue sites, 4) review of experimental trials, 5) assessment of new pasture species, 6) soil biology for early trajectory pathway, 7) Rhizobia, 7) pest plants Galenia and Coolatai
Australia (Central Queensland)	General pasture	Review information about management of rehabilitated pastures	Literature review and some pasture and soil data from Queensland coal mines	(Grigg et al., 2000)	Relationship between Rainfall-Use Efficiency and carrying capacity. Nutritional values of pasture on rehabilitated land. Relationship between root basal area and total-above dry matter for rehabilitated pastures. Relationship between projected cover and total above ground dry matter for rehabilitated pastures. Chemical characteristics of soil at two rehabilitation sites.

Appendix Table 2. Example tools to accomplish and/or demonstrate reference milestones relevant to a grazing PMLU

Reference milestone	Example Tool(s)
Landform development and reshaping/reprofiling [As part of a broader suite of landform design investigations (e.g., landform evolution modelling), the function of the landform with regards to its post-mining land use of grazing must be considered.]	Land suitability assessment (see *Short 2023 and* (DSITI and DNRM, 2015) ; Landform evolution modelling (Hancock et al., 2021) including consideration to the appropriate slope gradient and length (Trevaskis & Trotter, 2022)

<table>
<tr><th>Reference milestone</th><th>Example Tool(s)</th></tr>
<tr><td>Surface preparation
[Application of topsoil/growth medium, fertiliser and ameliorants]</td><td>Land suitability assessment (see Short 2023 and (DSITI and DNRM, 2015)</td></tr>
<tr><td>Revegetation
[Seeding of pasture species, application of fertiliser and ameliorants]</td><td>Land Condition Assessment Tool (LCAT), landscape functionality analysis (LFA), Stocktake, VEGMACHINE</td></tr>
<tr><td>Achievement of surface requirements
[Monitoring to determine if vegetation is self-sustaining, species richness, diversity and density]</td><td rowspan="2">LCAT, LFA, Stocktake, VEGMACHINE
FORAGE Long-Term Carrying Capacity (LTCC), SWIFTSYND, GRASP modelling, and AussieGRASS model</td></tr>
<tr><td>Achievement of post-mining land use to stable condition
[Demonstrate land is safe, structurally stable, does not cause environmental harm and is able to sustain the PMLU]</td></tr>
</table>

Appendix Table 3. Key features of monitoring tools for land being rehabilitated to grazing

Name of tool	Land Condition Assessment Tool (LCAT)	Stocktake	VegMachine	Landscape Function Analysis (LFA)
Who this tool is for?	All land managers/professionals: graziers, government workers such as environmental officers, environmental consultants, rehabilitation professionals.	Mostly appears to be targeted at graziers – simple app (Stocktake GLM)	"Government agencies, natural resource management (NRM) groups and individual pastoralists" (Beutel et al., 2019)	Originally developed for monitoring rangelands and updated to specifically monitor mine rehabilitation
App/Platform /Manual	Access to LCAT is via an ESRI 123 Survey requiring an ArcGIS licence. Access to a use specific licence may be available via DAF. Proponents may contact DAF for access.	App	Online tool	Manual
Questions this tool answers	What condition is the land currently in?	What condition is the land currently in?	How has the landscape changed over decades?	How effectively is a piece of land operating as a biophysical system? Does the landscape "leak" resources (such as water, topsoil, organic matter and propagules) and lose function? Or is there a gain in function?
What this tool does	LCAT enables the rapid and consistent collection of standardised land condition data and generation of objective results.	Aims to "provide grazing land managers with a practical, systematic way to assess land condition and long-term carrying capacity, and to calculate short-term forage budgets." (Queensland Department of Primary Industries and Fisheries, 2004)	Uses satellite data to calculate vegetation and fire scars over a timeseries for a user-drawn polygon on a map of Queensland	"Assesses the landscape function of a piece of land by characterising processes involved in the transport, utilisation and cycling of scarce and limiting resources, such as water, topsoil, organic matter and propagules, in space and time. This approach specifically examines the functioning of a landscape and is differentiated from biological composition and structure that have been the traditionally assessed characteristics."

Name of tool	Land Condition Assessment Tool (LCAT)	Stocktake	VegMachine	Landscape Function Analysis (LFA)
Inputs	"LCAT app user answers a series of questions by selecting pictograms (stylised pictures) representing land condition values—such as, pasture composition, density and 'quality', ground cover, erosion processes, pest plant impacts and vegetation densities. Impacts from natural events or management practices such as drought and total grazing pressure can be recorded to inform current land condition and risks" (Department of Environment and Science, 2021) This information is input at the paddock scale.	Stocktake field assessment involves, for each land type, in each paddock, taking two photos (trayback and landscape) at a fixed site, and using a Field Recording Sheet, to assess and rate the overall condition of key resource indicators (soil condition, pasture condition, tree basal area, pasture yield and % yield unpalatable)	Satellite imagery, user drawn polygon, rainfall data (already provided)	"1. Description of the geographic setting of the site. 2. Characterisation of landscape organization, the spatial distribution of the fertile-patches and interpatches. 3. The soil surface assessment (SSA, via simple visual indicators) of each of the patch/inter-patch types identified in step 2." "These include measures of: • Soil Cover • Perennial grass basal and tree • and shrub foliage cover • Litter cover • Litter cover, origin and degree of decomposition • Cryptogam cover • Crust broken-ness • Erosion type & severity • Deposited materials • Surface roughness • Surface resistance to disturb. • Slake test • Soil texture"
Outputs	15 calibrated results derived from a minimum set of long-term land condition and other indicators (inputs). These, include an ABCD site rating aligned to grazing land management and ecological principles, a numeric site score, an indicative pasture biomass (kg/ha), a range of potential site/landscape 'hazards' associated with water quality, fire and ecological impacts.	• Land Condition Report • Property Carrying Capacity Report • Trends	Graphs of vegetation and fire scars over time (monthly intervals available)	Landscape organisation indices, including: • Number of patch zones/10 metres • Total Patch area • Patch Area Index • Average inter-patch length and range • Landscape Organisation Index (derived by dividing the sum of the patch zones by the length of the transect line). Indicators of soil surface: • Stability • Infiltration/Runoff • Nutrient Cycling.

Name of tool	Land Condition Assessment Tool (LCAT)	Stocktake	VegMachine	Landscape Function Analysis (LFA)
Can show that erosion is acceptable	Yes, records erosion features and stability, ground cover and components and generates erosion risk and landscape stability results.	Yes, some characterisation of erosion.	Yes – can estimate soil erosion rates (Queensland Gov, 2022).	Yes, assesses soil stability, runoff and infiltration.
Monitors invasive flora and fauna	Yes, monitors pasture composition. Ability to record species listed in the Queensland Biosecurity Act and Regulation	Somewhat, to the extent that 'weeds' are monitored, where a weed is taken to be a plant growing out of place. Does not monitor pasture composition.	No	No, does not monitor pasture composition
Evaluates fire risk	Yes, generates a 'Fire potential' result. Calculated from a range of ground layer characteristics, slope and woody vegetation inputs	No	No. Evaluates fire scars but does not estimate fire hazard	No, no fire hazard report – however, it does contain methods for resilience to disturbance
Shows land grows sufficient pasture to sustain cattle	Gives indication of pasture growth which can be put into carrying capacity/pasture modelling tools. Calculates "indicative biomass", and sends grazing alert when biomass is low.	Yes, outputs carrying capacity report	No. Can show vegetation coverage but not biomass and therefore not whether vegetation is appropriate for cattle	No, little indication of whether it can sustain cattle – but monitoring over time with this method when cattle have been introduced will indicate sustainability – and method also gives indices of self-sustainability – which is useful for adaptive management. The premise is that if the 3 indices (stability, infiltration and nutrient cycling) are functioning than pasture growth is being sustained.
Specificity to rehabilitated mined land	Developer considers the LCAT is suitable for mined land. Has tested dozens of scenarios and developer is open to adaptation for mined land if necessary. No limitations for its implementation on mined land have been reported.	No, but has potential to be used in its current form.	No, but has potential to be used in its current form.	Yes, adapted for mined land
Sources:	(Hassett, 2021; Hassett, 2022)	(Queensland Department of Primary Industries and Fisheries, 2004)	(Beutel et al., 2019)	(Tongway and Hindley, 2004)

Appendix Table 4. Modelling tools to demonstrate that land achieves a stable condition

Name of tool	FORAGE Long-Term Carrying Capacity (LTCC)	SWIFTSYND	GRASP modelling	AussieGRASS model
Who this tool is for	"FORAGE LTCC is designed to be used by extension providers in consultation with graziers. In addition, the LTCC report can be used to guide grazing property purchases or sales and to assist in stock and property management decisions." Graziers can access FORAGE through the new myforage website.	Not noted – no platform publicly available suggests not for general use. Laboratory tasks suggest need for specialised personnel/equipment.	Pasture scientists	Unknown
Questions this tool answers	"How many livestock will a paddock or property be able to support over a long period (i.e., decades) without running down the property's land condition?"	What is the estimated rate of pasture growth? What are the levels of the two major indicators of degradation risk, i.e., pasture utilisation and surface cover?	How much does pasture grow given a certain land type?	AussieGRASS provides long-term time-series of rainfall and pasture growth information, as well as projections for the season ahead, which are useful for forage budgeting, assessing the impacts of drought, and bushfire risk.
What this tool does	The FORAGE Long-Term Carrying Capacity report provides an assessment of the estimated long-term "safe" carrying capacity (LTCC) for your property. LTCC in this report is the "number of livestock that a paddock or property can support over a long period (i.e., decades) without running down the property's land condition". The LTCC is measured as the total adult equivalents (AEs); 450 kg cattle consuming 8kg DM/day) that can be safely carried for a paddock or property. LTCC is also shown as ha per AE unit." It requires one to have previously assessed the land condition, as the land's condition rating (ABCD) is required to interpret the model. NB. Forage also has annual rainfall, simulated pasture growth and simulated ground cover reports.	The primary aim of SWIFTSYND is to derive parameters to run the GRASP model for the widest possible range of communities and soil/species combinations throughout northern Australia. The main parameter sought is the water-use-efficiency of the pasture, that is, the amount of above ground dry matter production per mm of transpiration. SWIFTSYND is based upon the GRASP model, and SWIFTSYND derives parameters to calibrate the GRASP model.	GRASP is "simulation modelling" that helps to "determine the impacts of grazing pressure, climate, pasture condition and trees on grazing land types"	"AussieGRASS is essentially a spatial implementation of Queensland Government GRASP (Grass Production) model". "Aussie Grass is a combination of rainfall analyses, seasonal climate forecasts, satellite and terrestrial monitoring, and simulation models of relevant biological processes. This will provide a rational basis for large-scale management decisions by graziers, extension workers, land resource managers, bureaucrats, and politicians. Aussie GRASS national spatial modelling framework allows agricultural simulation models to be run at a continental scale on a 0.05 degree (~5 km) grid. The simulation model currently in use by the Aussie GRASS project is the GRASP pasture model"

Name of tool	FORAGE Long-Term Carrying Capacity (LTCC)	SWIFTSYND	GRASP modelling	AussieGRASS model
Inputs	Location of a paddock through lot identified or use of the geolocation tool. Land condition (via LCAT).	Climate: • rainfall Soils • gravimetric moisture content • soil bulk density Plants • green and dead plant cover • dry matter yield of grass and forbs • dry matter yield of leaf, stem and inflorescence for each grass group sampled • total % nitrogen • pasture basal area • tree basal area	"Climate data, biophysical parameters and grazing management decisions such as burning and stocking rate"	Climate Soils Trees Normalised Difference Vegetation Index Stocking Rate Burning (All of above via remote imaging) User must select a time period and location.
Outputs	Users "will receive 3 files by email: a multiple page "Long-Term Carrying Capacity" report (PDF) an Excel spreadsheet showing the long-term carrying capacity for all the paddocks. The spreadsheet can be used to calculate long-term carrying capacity for paddocks under different land condition states." Outputs also include "an Excel spreadsheet showing long-term carrying capacity on a paddock and land type basis."	Calibrated pasture growth GRASP model for a given study site	• Historical pasture growth • Conditional probability analysis • Simulation of pasture growth for different land-types • Runoff for different soil types • Variable dilution of available nitrogen	• Monthly rainfall and pasture (growth, biomass, curing index and grass fire risk) • Rainfall and pasture growth percentiles • Pasture biomass percentiles • Seasonal pasture growth 3-month outlook (probability) and skill score • Potential flow to stream (runoff) percentiles • Potential flow to stream (runoff) outlook • Forecast curing and ground cover anomalies
Sources:	(Queensland Governmment, 2014)	(Day and Philp, 2000)	(Queensland Department of Environment and Resource Management, 2010)	(Carter et al., 2000) https://www.longpaddock.qld.gov.au/