Final report

Defining the pathway for remediating mining land for productive, profitable, and sustainable beef production

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Abstract

This project has undertaken to define a pathway for remediating mining land for productive, profitable, and sustainable beef production in the Bowen Basin. Coal mining companies own or manage up to 760K hectares in this region, comprising 557K hectares of granted mining lease (ML) and an additional 202,931 hectares that sit adjacent to ML areas. Though 90% of this area historically supported grazing, mining operations exclude commercial livestock production from most of the ML land, reducing the livestock carrying capacity within the Bowen Basin by more than 100K Adult Equivalents (AE). Though the coal mining sector will likely relinquish this land for livestock production through the mine closure process, its mining and exploration activities are anticipated to disturb 256,177 hectares of ML land by 2050. Despite a common expectation grazing land will be rehabilitated for this same end use, current topsoil deficits of 30-50% relative to requirements can necessitate the use of sodic and dispersive spoil materials that may not accommodate conventional grazing practices on inevitably sloped reconstructed landforms. The mining industry requires a scalable system for achieving viable and productive livestock production on these sloped landforms if it is to create as much grazing post-mining land use (PMLU) as possible. This project has undertaken to define a silvopastoral model for achieving this outcome. First, the opportunity the mine closure process affords the livestock industry was described in terms of the quantum and biophysical characteristics of mining land. Second, the project scoped and developed a potential silvopastoral model for remediating undisturbed mining land and achieving completion criteria for viable and productive grazing PMLU on sloped landforms. The model's development was informed from an inventory of livestock management practices gathered from surveys and interviews of 14 graziers who have remediated degraded land-types in the Bowen Basin. The project has relied on historical property data and the peer-reviewed literature to verify practice effectiveness. An appreciation of the biophysical context of mining land types was used to clarify the obstacles for the proposed silvopastoral model's implementation ("implementation gap"). The project anticipates the research and development requirements for overcoming or minimising this implementation gap. It concludes by considering the use of new and emerging digital technologies to manage the model's implementation.

Executive summary

Background

The coal mining industry currently owns or manages more than 557,000 hectares of land under granted mining lease (ML) in Queensland's Bowen Basin.[1] Coal mining companies also acquire large areas adjacent to their ML land. Since approximately 90% of their land was historically used for livestock production, the exclusion of commercial grazing activities from most of ML areas represents an opportunity cost to the livestock of about $60.7 million/year if one assumes a carrying capacity of 1 Adult Equivalent (AE)/5 hectares (i.e. 111,400 AE).[2] In Queensland, coal mining and exploration activities had disturbed 142,965 hectares of ML land before 2020 and this is expected to increase to 256,177 hectares by 2050. A 30-50% topsoil deficit relative to rehabilitation requirements for open cut mining presents a significant challenge for returning this land to grazing, necessitating the establishment of a feedbase on elevated sloped landforms often covered with sodic and dispersive spoil materials.[3] Without a scalable solution for achieving viable and productive grazing as a post mining land use (PMLU) on these landforms, the mining industry is likely to prioritise its rehabilitation for alternative PLMU. On the one hand, the loss of historical grazing land represents a continuing opportunity cost to the livestock industry. On the other hand, the mining industry's need to find management practices for sloped, potentially erosive landforms presents a potential business opportunity for livestock producers to partner with the mining industry in achieving better outcomes for grazing as a profitable, productive, and sustainable PLMU.

The potential scope for the livestock industry's servicing of mining land extends beyond supporting the achievement of grazing PMLU on reconstructed landforms. First, an opportunity exists for the livestock industry to service the remediation of larger areas of historically degraded mining owned grazing land by implementing practices that sequester carbon, build biodiversity, and improve productivity. Second, since land packages relinquished through the mine closure process will contain rehabilitated areas, scope exists for the livestock industry to develop a scalable model for integrating the sustainable management of these areas within larger business-as-usual operations.

The project has undertaken to define a scalable model for partnering with the mining industry to achieve viable and productive beef production on rehabilitated grazing PMLU landforms and achieve additional environmental and production objectives on degraded land under mining ownership or management. This model is informed and developed from an inventory of practices demonstrated to remediate degraded land within the Bowen Basin. A research strategy is recommended for overcoming obstacles that present an "implementation gap" for the model's implementation.

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[1] This report refers to mining companies as "owning or managing" land. Though these companies often own freehold land, they also enter into various kinds of lease agreements with current landholders to gain access to underlying coal measures.

[2] For a review of carrying capacity with respect to land types and localities in the Bowen Basin see Grigg *et al.* (2001)

[3] This project has not found published surveys of topsoil reserves relative to rehabilitation requirements. The 30-50% used here is an estimate provided by DES (Business Centre Coal, Email received: 4th April, 2022). It should be acknowledged, `however, that the present deficits reflect the results of past practice. Since mining companies and the Queensland Government are now aware of this problem, it is expected that deficits of this magnitude will not characterise future mining operations.

Objectives

The objectives of the project were to:

1. Define the opportunity the mine closure process affords the beef industry in the Bowen Basin.
2. Identify and describe an inventory of practices used to remediate land in this region.
3. Describe the "implementation gap" for implementing a scalable beef production model as a rehabilitation service for mining land.
4. Assess opportunities for overcoming this implementation gap using digital technologies.
5. Deliver a research plan to secure the information, technology, and management practices required for overcoming or minimising this implementation gap.

Methodology

The project undertook the following activities to achieve its objectives:

1. A desktop study and consultations with mining company partners to assess the opportunity the mine closure process affords the livestock industry within the Bowen Basin. As part of this assessment, the biophysical context for anticipated practice implementation was described.
2. Graziers were surveyed to identify an inventory of practices that remediate degraded land.
3. The inventory of practices was used to inform the development of a scalable silvopastoral model for providing a pathway that remediates undisturbed and disturbed mining land.
4. Obstacles that present an implementation gap for this model's application on mining land were identified and assessed.
5. The project considered how new and emerging digital technologies may facilitate the model's implementation during the mine closure process.

Results/key findings

The project has revealed that up to 760,627 hectares of predominantly grazing land (*c.* 90%) is owned or managed by mining companies within the Bowen Basin. This area comprises 557,696 hectares held under granted ML from which consistent commercial livestock production activities are largely excluded. A remaining 202,931 hectares of mining owned or managed land sits adjacent to ML areas. This adjacent land remains undisturbed, though degraded by historically sub-optimal grazing management practices.

The exclusion of commercial grazing operations from most ML land represents an opportunity cost of nearly $60.8 million/year to the livestock industry, reducing the latter's potential herd size by about 111,400 AE.[4] Though companies may apply to extend ML expiry dates, the total 557,696 hectares under ML are currently scheduled to expire at a relatively constant rate over a 30-year period. As mines close, a large proportion of ML will remain undisturbed and suitable for grazing, but the availability of disturbed areas to the livestock industry will depend on the proportion of this land rehabilitated for grazing as the PMLU. One can assume that the adjacent undisturbed land holdings will become available at a similar rate to ML land.

Mining activities and exploration are anticipated to disturb about 256,177 hectares by 2050. The proportion of this area that will be rehabilitated for grazing, and its relative productivity remains unknown. The project has identified three current challenges for the mining industry's rehabilitation of disturbed land for viable and productive grazing PMLU. First, it lacks specific design principles for engineering functional grazing PMLU landforms. These design principles would allow mining

[4] This assumes an annualised land value of $109/ha (De Valck *et al.*, 2021) and an average carrying capacity of 1 AE/5 hectares.

operations to threshold out disturbed land that may never achieve grazing PMLU completion criteria. Second, the industry does not yet have scientifically verified and livestock industry supported grazing PMLU completion criteria. Third, a 30-50% topsoil deficit relative to requirements sometimes makes it necessary to use sodic and dispersive spoil materials to cover sloped landforms. These problematic materials challenge the establishment and management of groundcover on erosive slopes, increasing the difficulty of achieving sustainable grazing PMLU. This project primarily focuses on addressing the third challenge, namely the development of a scalable silvopastoral model for servicing the achievement of viable grazing PMLU on sloped landforms.

To guide the development of a model for the servicing of mining land, the project assembled an inventory of practices that have been used by graziers to remediate degraded land in the Bowen Basin. Fourteen graziers managing more than 120,000 hectares of grazing land within this region participated in an online survey distributed to more than 70 graziers. Where historical property data was unavailable to verify practice effectiveness, the project consulted the peer-reviewed literature. The identified and described practices were organised under three broad practice categories, namely (a) Silvopastoralism, (b) Adaptive Grazing Management, and (c) Missional Grazing Activities.

The project relied on the assembled inventory of practices to develop a digitally enabled silvopastoral model for achieving completion criteria for viable and productive grazing PMLU land and remediating undisturbed historically degraded grazing land. It seeks to offset the potentially qualified productivity of rehabilitated land by creating alternative revenue streams from commercially relevant tree-lined contours. Though the application of the inventory of practices to undisturbed mining land is considered business as usual by practitioners, the project identified obstacles collectively described as an implementation gap for the proposed silvopastoral model's servicing of rehabilitated landforms. It considers the potential for new and emerging digital technologies to overcome or minimise this gap.

Benefits to industry

The project's outcomes benefit the livestock industry by clarifying an opportunity to develop a digitally enabled scalable silvopastoral model that (a) facilitates the rehabilitation of as much land for grazing PMLU as possible by supporting the achievement of completion criteria for viable and productive livestock on sloped land and (b) services carbon and biodiversity objectives for 202,931 hectares of undisturbed grazing land owned or managed by mining companies adjacent to ML areas, and undisturbed ML land as this becomes available for livestock production. The validation of the proposed digitally enabled silvopastoral model is intended to provide a business opportunity for graziers to gain financially from the mine closure process and produce an educational model for certifying competency for model implementation. The model will also provide livestock producers with confidence to acquire mining land that contains rehabilitated sloped landforms.

Future research and recommendations

To provide a service that supports the achievement of completion criteria for as much viable and productive grazing PMLU land as possible and achieves additional carbon sequestration and biodiversity objectives, the project recommends the development and validation of a scalable digitally enabled silvopastoral model for delivering environmental services. The research modules required for delivering this outcome include:

1. **Collaborate with the coal mining industry to define mutually acceptable and scientifically verified rehabilitation completion criteria for viable grazing PMLU.** The definition of criteria that support livestock production on a range of sloped landforms will clarify (a) the

development of a silvopastoral approach for supporting their achievement and (b) the required management practices and expected productivity of rehabilitated landforms.

2. **Development of design principles that guide the creation of fit-for-purpose grazing PMLU landforms in the Bowen Basin**. Current sustainable landform design guidelines do not prescribe design principles for the creation of functional landforms for viable grazing PMLU. This report recommends that the livestock industry collaborate with the mining industry to use completion criteria defined in (1) and best practice adaptive grazing management practices to inform the expansion of guidelines to include design principles for creating functional landforms that support sustainable and viable grazing PMLU on sloped land.
3. **Development of a grazing management system for achieving viable grazing PMLU completion criteria on sloped landforms.** There is a lack of basic agronomic information to guide grazing management decisions aimed at optimising the persistence, regrowth, and competitive advantage of plant species used for rehabilitating mining land. In part, this lack of data may account for conflicting results in comparative studies of rotational and continuous grazing systems in Northern Australia. Basic controlled environment defoliation experiments should be undertaken to determine the optimal defoliation intervals and heights for maintaining pasture groundcover, productivity, and diversity on sloped landforms. The data obtained from these studies will form the basis of a decision-making matrix for grazing rehabilitated landforms.
4. **Evaluate commercially relevant tree species and ideal silvopasture architecture for rehabilitated landforms.** Research should (a) review the success of commercially relevant tree species already planted in a range of spoil types in the Bowen Basin, (b) trial novel tree species in a range of spoil types, and (c) develop a decision-making matrix for silvopasture layout relative to slope and spoil types for increasing water filtration and maintaining groundcover.
5. **Configure a scalable silvopastoral model for achieving viable and productive grazing PMLU completion criteria.** Drawing on the outcomes of Modules 1 – 4, research should configure a scalable silvopastoral model for implementation on a range of sloped landforms that integrates the management of undisturbed and rehabilitated areas within a relinquishable land package.
6. **Develop a digital monitoring and livestock management platform for model implementation on rehabilitated landforms.** The integration of virtual fencing and remote sensing technologies may provide an opportunity to manage grazing in relation to interactions between slope, weather, spoil material and groundcover.
7. **Conduct a long-term pilot scale evaluation of a digitally enabled and adaptive silvopastoral model on a landform created fit-for-purpose for grazing PMLU.** A long-term (i.e., > 5 years) study is required to validate the proposed silvopastoral model's capacity for achieving viable grazing PMLU completion criteria on land designed for supporting this outcome.
8. **Develop an educational program for certifying competency for model implementation.** The unique biophysical characteristics of rehabilitated landforms, operational constraints on ML land, incorporation of commercially relevant tree crops, and the use of digital technologies necessitate an educational program to support model adoption.

The project recommends the development of a partnership between MDC and the coal mining industry through the Australian Coal Association Research Program (ACARP)[5] for undertaking these research modules.

[5] ACARP invests $15 million in research each year through a levy of 5c per tonne of saleable coal. It is 100% owned by the black coal industry and is eligible for receiving MDC co-funding. This project will deliver a research plan to secure the information, technology, and management practices required for deploying livestock production system practices to achieve specified goals.

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1. Background

Approximately 90% of the 557,696 hectares of land coal mining companies hold under granted ML in Queensland's Bowen Basin was historically used for livestock production (Evans *et al*., 2015). Coal mining companies self-reported that their operations (including exploratory activities) had disturbed 142,965 hectares of land in Queensland by December 2019, most of which occurred in the Bowen Basin.[6] Assuming that these operations will continue to disturb land at a rate of 3,652 hectares year^{-1}, more than 256,177 hectares of land will require rehabilitation by 2050.[7] Unfortunately, current publicly available disturbance figures do not distinguish between mining disturbance caused by exploration or coal extraction methodologies.[8]

The most drastic impact to grazing land is caused by open cut extraction methods.[9] Despite a common social expectation that this land will be rehabilitated for this same end use, a 30-50% topsoil deficit relative to requirements can necessitate the use of sodic and dispersive spoil materials.[10] A reliance on these materials to cover elevated sloped reconstructed landforms increases the risk of erosion by challenging the establishment and maintenance of groundcover. Without a cost-effective means for achieving viable and productive grazing PMLU on sloped rehabilitated land, anecdotal evidence suggests that as much as 70% of land disturbed by open cut methods may be rehabilitated for lower value alternative PLMU.[11] The loss of this area to the livestock industry represents an opportunity cost of $109/ha year^{-1} for this region (De Valck *et al*., 2021). Further opportunity costs are incurred where the productivity of the remaining area rehabilitated for grazing purposes is less than its pre-mining potential.

In addition to the areas they disturb, coal mining companies own or manage large areas of grazing land that will remain undisturbed beyond mine closure. The companies partnering this project report that most of this land has been degraded by historically sub-optimal grazing practices. Constraints upon its present availability for livestock production depend on whether it sits within ML boundaries or adjacent to these. Though the mining companies interviewed within this project indicate that they generally exclude commercial grazing activities from most of their ML land, they tend to agist the land they own or manage

[6] *DES Business Centre Coal,* Email received 6th May 2021. More recent figures were not available at the time of writing.

[7] This estimate of 3,652 hectares of disturbance year^{-1} by coal mining is based upon the following assumptions: (a) the broader mining industry disturbs land at a rate of 5,619 hectares/year (EPA 2007) and (b) coal mining accounts for about 65% of mining disturbance in Queensland (Rolfe *et al*., 2018). DES confirmed that there are no more recent estimates for annual mining disturbance than that published in EPA (2007) (DES, Business Centre Coal, Email received on 5th April 2022).

[8] Since land disturbed by exploratory activities (i.e. the establishment of graded roads and bore holes), may initially fall outside ML boundaries, the disturbed area should not be thought of as confined to ML land.

[9] The disturbance caused by exploration activities is mostly limited to the grading of roads and drilling of bore holes across grazing areas. The disturbance caused by underground coal mining and its relevance for livestock production is addressed in Appendix 8.3.

[10] Mining company partners of this project estimate that a topsoil deficit within range is not unusual on many coal mining sites in the Bowen Basin.

[11] The figure of 70% was reported by one of the project's mining company partners. The primary factor for determining how much land is rehabilitated for grazing PMLU relates to the cost of regrading spoil dumps to appropriate gradients. It seems likely that companies will create more grazing PMLU where the dumping of spoil pre-empts its regrading for this purpose.

adjacent to ML areas to previous or ML perimeter landholders. The mining companies are under no obligation to improve this land and agistment agreements typically frame management expectations in terms of "best practice".[12]

Aware that livestock production systems have successfully restored ecosystem functionality on degraded land in the Bowen Basin, this project's mining partners expressed an interest in partnering with the livestock industry to adapt these systems for achieving viable grazing PMLU as a scalable topsoil building, carbon sequestering, and biodiversity building service. Livestock management practices proven to sequester carbon and build biodiversity could improve outcomes for the livestock industry from both undisturbed and disturbed land types while generating new sources of revenue for providing environmental services. The specific services this project attempts to develop include the following:

A. A scalable approach for livestock producers to deliver carbon and biodiversity building activities on undisturbed albeit historically degraded grazing land owned or managed by mining companies in the Bowen Basin.
B. The development of a rehabilitation service model for supporting the achievement of viable and productive grazing PMLU completion criteria.
C. A scalable model that provides livestock producers with the confidence to acquire relinquished mining land that contains parcellated areas rehabilitated for grazing purposes and other special management areas.[13]
D. An educational program that certifies operators as competent at model implementation on sloped rehabilitated landforms.

This project undertakes to evaluate the opportunity the coal mine closure process affords the livestock industry in the Bowen Basin. On the one hand, it draws on an inventory of practices used for remediating degraded land in the Basin to develop a scalable model for supporting the achievement of viable and productive grazing PMLU. On the other hand, it investigates how livestock production may be used to achieve environmental and production objectives for undisturbed mining land degraded by historically sub-optimal grazing management. The development of a comprehensive approach and ancillary education program for managing the different mining land types also aims to provide livestock producers greater confidence to acquire land that contains rehabilitated areas.

2. Objectives

This project focussed on developing a livestock production system that could (a) provide a business opportunity for offering the environmental services required for achieving viable and productive grazing PMLU completion criteria and (b) provide confidence for livestock producers to acquire disturbed and undisturbed mining land relinquished through the mine closure process. It has undertaken to achieve the following objectives.

[12] The agistment agreements are commercial-in-confidence so that it has not been possible to review the detailed expectations for how land is managed.

[13] Special management areas refer to land that is beyond complete rehabilitation (e.g. saline water-filled voids; contaminated areas) and cannot sustain a PMLU due to their inherent risk to people, animals, and the environment. Though these areas will be managed by the Queensland Government after relinquishment, they likely represent a perceived liability for future landholders. Queensland Government (2017).

2.1 The opportunity the mine closure process affords the livestock industry

An attempt has been made to define the opportunity that mine closure process affords the beef industry by quantifying four metrics, namely:

A. The area (hectares) of rehabilitated and undisturbed, albeit historically degraded land for future relinquishment that has relevance for livestock production,
B. The carbon and biodiversity goals (sequestration potential tonne/hectare, plant-animal species diversity and abundance) for implementing beef production as a revenue-generating rehabilitation service,
C. The potential grazing land (hectares) that may benefit from servicing and/or re-commercialising this land,
D. The direct or indirect revenue ($/hectare) pastoralists may receive by offering a rehabilitation/re-commercialisation service that achieves defined carbon and biodiversity goals

The project has successfully determined the areas of rehabilitated and undisturbed grazing areas that will become available for grazing purposes as they are relinquished through the mine closure process. Nevertheless, the project revealed that mining companies do not yet have well-defined carbon and biodiversity goals for land held under their ownership or management. There is an opportunity for the livestock industry to partner with coal mining partners to define realistic targets and develop a strategic approach for their achievement using the digitally enabled silvopastoral model proposed in this report. The lack of clear carbon and biodiversity targets makes it difficult to clarify the direct or indirect revenue pastoralists may receive for offering services that achieve such targets. Consequently, this project has undertaken to sketch out a potential business model whereby pastoralists may benefit from favourable agistment conditions, the provision of water and fencing infrastructure required to implement profitable adaptive grazing practices, and a mechanism for delivering certified carbon neutral beef production from mining owned or managed land.

1.2. The development of an inventory of practices that remediated degraded land types

The project aimed to uncover and develop an inventory of practices successfully used by pastoral operations to remediate land types within the Bowen Basin. From a review of peer-reviewed studies, it was anticipated that these practices would include adaptive grazing management (Shrestha *et al*., 2020), silviculture (Doran-Browne *et al*., 2018), minimisation of uniform mechanical and chemical disturbance (Teague and Kreuter, 2020), and revenue diversification to mitigate the overuse of resources for livestock production (e.g., use of dual-purpose trees; Fenster *et al*., 2021). The project has identified pastoral operations that have used a specific set of silvopastoral practices to successfully remediate degraded land in the Bowen Basin. These pastoralists were surveyed and interviewed to develop an inventory of practices that may have relevance for enhancing environmental services and livestock production on mining owned or managed land-types.

2.3 An assessment of the "implementation gap" for implementing scalable beef production as a rehabilitation service for re-commercialising land

The project sought to identify and rank obstacles to the adoption of the identified practices as a rehabilitation service and means for transitioning rehabilitated land under mining tenure to a production level that surpasses pre-mining levels. The project used its assembled inventory of practices to propose a scalable digitally enabled silvopastoral model for remediating mining owned or managed land for productive, profitable, and sustainable beef production. The proposed model was considered alongside the biophysical context of mining disturbed and undisturbed land types and mine site operational constraints to assess the challenges for its implementation.

2.4 The application of digital technologies for overcoming or minimising the implementation gap for using silvopastoralism to remediate mining land types

The project evaluated digital technologies that have potential for facilitating the scaled application of the proposed silvopastoral approach on mining land. The new and emerging technologies were considered in terms of their capacity to facilitating the overcoming of specific obstacles identified for the approach's implementation. This part of the project also assessed the development that is required to deploy these technologies within the proposed silvopastoral model.

2.5 Scoping and development of a research plan

The project has collaborated with the MLA and mining company partners to scope and develop a Phase 2 research plan for overcoming or minimising obstacles for the proposed silvopastoral model's implementation on mining land. It is proposed that MLA's Donor Company (MDC) partners with these mining company partners through the Australian Coal Association Research Program (ACARP) to deliver recommended research modules. ACARP invests $15 million in research each year through a levy of 5 cents/tonne of saleable coal. It is 100% owned by the black coal industry and is eligible for receiving MDC co-funding. This project will deliver a research plan to secure the information, technology, and management practices required for deploying livestock production system practices to achieve specified environmental and production goals.

3 Methodology

3.3 Estimation of the opportunity the mine closure process affords the beef industry

The project partnered with three mining companies operating a combined total of 20 open cut and underground coal mines the Bowen Basin. These companies provided the project with access to rehabilitation manuals and environmental managers to understand and clarify opportunities the mine closure process presents for the livestock industry.

The project consulted Gerygone to determine (a) the total area of land held under granted ML within the Bowen Basin and the respective expiry dates for these MLs and (b) the area of land owned or managed by coal mining companies that sits adjacent to the granted ML areas. Consultation with the project's mining company partners revealed that it was considered best practice to acquire land parcels that were partially overlapped by granted ML boundaries. Gerygone was used to identify and calculate the area of this land by using the Cadastre layer to:

A. Identify all rural properties that were contained within or overlapped ML boundaries by > 1 metre
B. The total ML area for coal extraction calculated from GeoResGlobe was subtracted from the area determined in (A) to estimate the area of undisturbed land mining companies own or manage adjacent to ML land.

Since the practice of acquiring land in this way was referred to as "best practice" the estimated land calculated in this way is expected to be an overestimate, though it seems worth noting that mining companies may own additional properties that are beyond identification using public registers. The project received advice from the Queensland Government and at least one partnering mining company that this was, however, the most accurate available means for calculating the total area of land owned or managed by mining companies within this region.

The area of land already disturbed by coal mining activities in the Bowen Basin were determined by assuming that:

A. Mining extraction and exploration activities have already disturbed 142,965 hectares of land before December 2019.[14]
B. The broader mining industry disturbs land at a rate of 5,619 hectares/year in Queensland (EPA 2007).[15]
C. The coal mining industry accounts for about 65% of this rate of disturbance (Rolfe *et al*., 2018).
D. On the basis of (B) and (C) the coal mining industry will continue to disturb land at a rate of 3,652 hectares/year until 2050.
E. Most of the disturbance by coal mining will occur within the Bowen Basin.

The limitations of the publicly available data include:

A. It does not distinguish between disturbance caused by exploration, open cut extraction, or underground mining methodologies.
B. The most recent figure for the rate of disturbance is from EPA (2007).

To describe the biophysical context of mining land types for the implementation of livestock production as a rehabilitation and/or re-commercialisation services, the project (a) consulted rehabilitation manuals used by two of the three mining partners (a third mining partner did not have a formal manual procedure for rehabilitating land for grazing purposes), (b) interviewed Environmental Managers of the partnering mining companies,

[14] *DES Business Coal Centre*. Email received 6th May 2021. DES has confirmed that more recent figures remain unavailable. Email received 4th April 2022.
[15] *Des Business Coal Centre* confirm that it does not have more recent figures for the rate of mining disturbance than the figure published in EPA (2007). Email received 4th April 2022.

and (c) reviewed the peer-review studies conducted on rehabilitated landforms in the Bowen Basin.

3.4 Inventory of practices used by pastoral operations that remediate land

3.4.1 Three exemplary pastoral operations representative of Bowen Basin land types identified

These operations were identified via a consideration of responses received from an online survey of graziers in the Bowen Basin (Appendix 8.1). The project used the survey results to prioritise the selection of pastoral operations that met a small number of criteria that indicate an operator has intentionally put in place systems processes to sequester carbon and/or build biodiversity (e.g., multiple paddocks/herd; frequency of livestock rotation; the use of flexible stocking density in response to climatic variation). The meeting of these criteria was subsequently verified electronically and via field visits. The project undertook to prioritise the selection of operations that have:

- Implemented system processes for at least 10 years to increase confidence in practice outcome metrics.
- Historical records relating to biophysical parameters and biodiversity.
- Where historical records are non-existent, visual comparisons are available for relevant biophysical metrics for managed land versus adjacent degraded land under conventional management strategies.

Priority was also given to identifying these exemplary operations that represent three different land types within the Bowen Basin to build a scalable livestock production system for application across rehabilitated land types within this region.

3.4.2 Up to 24 beef operations surveyed

The project developed an online survey that received human research ethics approval through Central Queensland University (Application ID: 0000023279). This survey is included within this report as Appendix 8.1. The project employed a voluntary selection process from a pool of pastoralists obtained through consultation with MLA, the Fitzroy Basin Association, NQ Dry Tropics, the Queensland Department of Agriculture and Fisheries, the Leucaena Network, RSC, and other livestock industry consultants. Several of these entities offered to send an invitation to participate in the online survey via their mailing lists.

The project followed up respondents who had implemented practices for > 5 years via phone interviews, asking a series of questions to further elucidate practices, decision making, and to verify the success of practice implementation.

3.4.3 Successful remediation practices identified and documented

Online surveys, phone interviews, emails, and in-field interviews were used to identify and document practices participants regarded as successful at remediating degraded land within the Bowen Basin. The project has also consulted the peer-reviewed literature to gather empirical support for the practices and to identify additional silvopastoral management practices that may have potential for contributing to the rehabilitation of mining land but are not yet widely implemented by graziers within the Bowen Basin.

The project relied on the Full Carbon Accounting Model (FullCAM) to estimate the carbon sequestration potential for growing 20% tree canopy cover within the localities of surveyed practitioners. FullCAM is a calculation tool for modelling Australia's greenhouse gas emissions from the land sector and is used is used in Australia's National Greenhouse Gas Accounts for the land use, land use change and forestry sectors. Results from modelling are used to produce the annual totals for Australia's National Inventory Reports.

The modelling considered "mixed species environmental plantings of > 1500 stems/hectare" over 20% of properties. "Mixed species environmental plantings" was selected because it is the method required for obtaining financial returns via the Australian Government's *Carbon + Biodiversity Pilot program* (Australian Government 2021). Belt-plantings were chosen because studies have demonstrated that biomass carbon sequestration rates are higher for this approach than plantings established in blocks (Paul *et al*., 2015). Paul *et al* (2015) cites experiments that demonstrate trees on outer belt rows grow 2 to 5 times faster than those within inner belt rows. The increased growth rates for these trees were attributed to their greater access to light and less competition for water with adjacent trees.

The growth of trees was modelled over a 30-year period to include the peek-rate of carbon sequestration at *c*. 25 years because this began to slow down (Doran-Browne *et al*., 2018). The project undertook a high-level evaluation of the extent to which carbon sequestered in tree belts could offset enteric methane emissions the livestock operations on each reported property. Enteric methane emissions were calculated using the following equations and assumptions:

Dry Matter Intake (DMI) = 1:185 + 0:00454W - 0:0000026W^2 + 0:315LW)^2 (Rolfe *et al*., 2010)

Where W = liveweight (kg) and LW = liveweight gain day^{-1} (kg)

The project assumed that AEU (450kg steer) gained weight at 0.4kg day^{-1}.

Individual animal enteric methane emissions (EME)= (20.7 x DMI)/1000 (Charmley *et al*., 2016)

Whole property annual enteric methane emissions: EME x SR x 365

SR = the property AEU stocking rate self-reported by surveyed practitioners.

3.4.4 Inventory of remediation practices detailed

The project draws on the available data gathered from surveyed graziers and the peer-reviewed literature to verify the effectiveness of practices identified (Appendix 8.2) before these were included within an inventory of such practices for potential application to rehabilitate and/or re-commercialise mining land. The project documented these practices within the context of the participant-defined strategic objectives for which they were implemented (e.g., increase ground cover, remediate scald patches, increase biodiversity etc). Where collected data was inconclusive at establishing whether implemented practices successfully remediated degraded land, the peer-reviewed literature was consulted.

4 Results

4.3 The opportunity the mine closure process affords the beef industry within Queensland's Bowen Basin

An understanding of the coal mine closure process provides context for appreciating the opportunity it affords the livestock industry. Mine-closure planning commences prior to the commencement of mining activities. The submission to the Department of Natural Resources, Mines and Energy (DNRME) of a company's application for a granted ML to obtain the rights for extracting the underlying sub-surface coal measures must occur alongside an application to DES for an amendment to an Environmental Authority (EA) that covered previous exploratory work to undertake the necessary environmentally relevant activities (ERA; Qld Govt, 2020).[16] Within Queensland, the State Government requires this EA to, among other things, describe how land disturbed by mining activities will be rehabilitated, the post-mining land use (PMLU) for which it will be rehabilitated, and the criteria by which the completion of rehabilitation will be measured (EPA 1994). The company must assess, to the Government's satisfaction, what residual risk applies to the relevant designated PLMUs and make payment to address risks that materialise. Once the Government is satisfied that the rehabilitation criteria agreed to within the EA have been achieved and a sufficient residual risk payment has been made, it can approve the mining company's application to surrender its ML and EA.[17] Upon approval, the company may relinquish its ownership of the land. The mining operation has closed.[18]

This understanding of the mine closure process provides context for appreciating the opportunity it affords the livestock industry within the Bowen Basin. The opportunity can be described in terms of (a) the quantum of land types currently owned or managed by coal mining companies that have immediate or future relevance for livestock production, (b) the biophysical and operational constraints that apply to these land types and their implications for grazing pre- and post-relinquishment, (c) the specific environmental and rehabilitation service opportunities mining owned or managed land may offer to the livestock industry during the closure process, and (d) the potential business model for developing a partnership between the livestock and mining industries that remediates mining land for productive, profitable, and sustainable beef production as a post-mining land use.

This project considers the opportunity mining land affords the livestock industry from the perspective of:

[16] Depending on how it perceives the proposed activities level of impact, DES may require the company submit a far more comprehensive Environmental Impact Statement (EIS).
[17] The Queensland Government needs to ensure that it has sufficient funds to manage, rehabilitate, restore and protect the environment should a residual risk occur. The EP Act provides the administering authority rights to secure such funds through a residual risk payment as part of a surrender application. Queensland Resources Council (2017), Rehabilitation and Relinquishment [online] Available at: https://www.qrc.org.au/policies/rehabilitation/ [Accessed 3rd February 2022]
[18] For more information on the legislation relating to mine closure in Queensland, see Queensland Government (2017) and Queensland Resources Council (2017).

A. The *pre-closure* opportunity for livestock producers to implement a scalable digitally enabled silvopastoral model for remediating large areas of undisturbed yet degraded grazing land. This land sits both within and adjacent to ML areas.
B. The *pre-closure* opportunity for the livestock industry to partner with mining companies in developing a cost-effective scalable model for achieving viable and productive grazing PMLU on sloped land, increasing the proportion of disturbed land rehabilitated for this purpose.
C. The *post-closure* potential for a digitally enabled silvopastoral model to provide producers with the confidence to acquire and manage relinquished land that contains sloped rehabilitated land.

To anticipate the specific opportunities this project identifies for the livestock industry, livestock producers may benefit from:

A. Implementing a digitally enabled silvopastoral model that supports the achievement of viable and productive grazing PMLU completion criteria by delivering required environmental services and economic activity on sloped landforms.
B. Implementing a digitally enabled silvopastoral model that achieves carbon and biodiversity objectives in return for affordable leasing arrangements, the provision of water and fencing infrastructure that supports adaptive grazing practices, and certification as operating carbon neutral livestock production on these areas.
C. Leasing arrangements that provide a clear pathway to the acquisition of relinquishable land.
D. A model that provides producers with the confidence to acquire and manage relinquished mining land that contains parcels of rehabilitated landforms.

3.1.1 Quantum, type, and availability for livestock production of land owned or managed by coal mining companies in the Bowen Basin

The mining of coal from the Bowen Basin commenced in the early 20th Century at the Blair Athol and Collinsville mines (Dunne 1950). Since this time, the industry's footprint has expanded across a substantial area in pursuit of coal measures that extend almost 600km from Collinsville in the North to the Dawson River south of Theodore (Figure 1; Dunne 1950). Mining companies either acquire land or negotiate leasing arrangements with landholders. Though most of this land is held under ML, they also acquire or lease land packages that overlap with ML boundaries.

3.1.1.1 Land held under granted mining lease

Coal mining companies apply for the Queensland Government to grant an ML over an area it wishes to undertake coal extraction activities.[19] The granting of an ML provides the company with the sub-surface rights for extracting coal underlying the relevant area. It does not necessarily, however, grant the company with permission to disturb the land surface. Unless the company owns this land, it negotiates a separate agreement with the landholder to obtain the surface rights for areas it needs to disturb to achieve the extraction, processing, and transport of coal (Bodenmann *et al*., 2012). Upon successful

[19] This application follows the completion of a process by which a mining company has successfully obtained an Exploration for Coal Permit (ECT) and a Mineral Development Licence (MDL). Queensland Government 2020.

negotiation, the Queensland Government will amend the ML to include the area of surface rights. The area covered by surface rights within a granted ML is the area the mining activity may disturb and require subsequent rehabilitation.[20]

In 2021, MLs granted for coal mining covered 557,696 hectares of land within the Bowen Basin (Figure 1; GeoResGlobe, 2021).

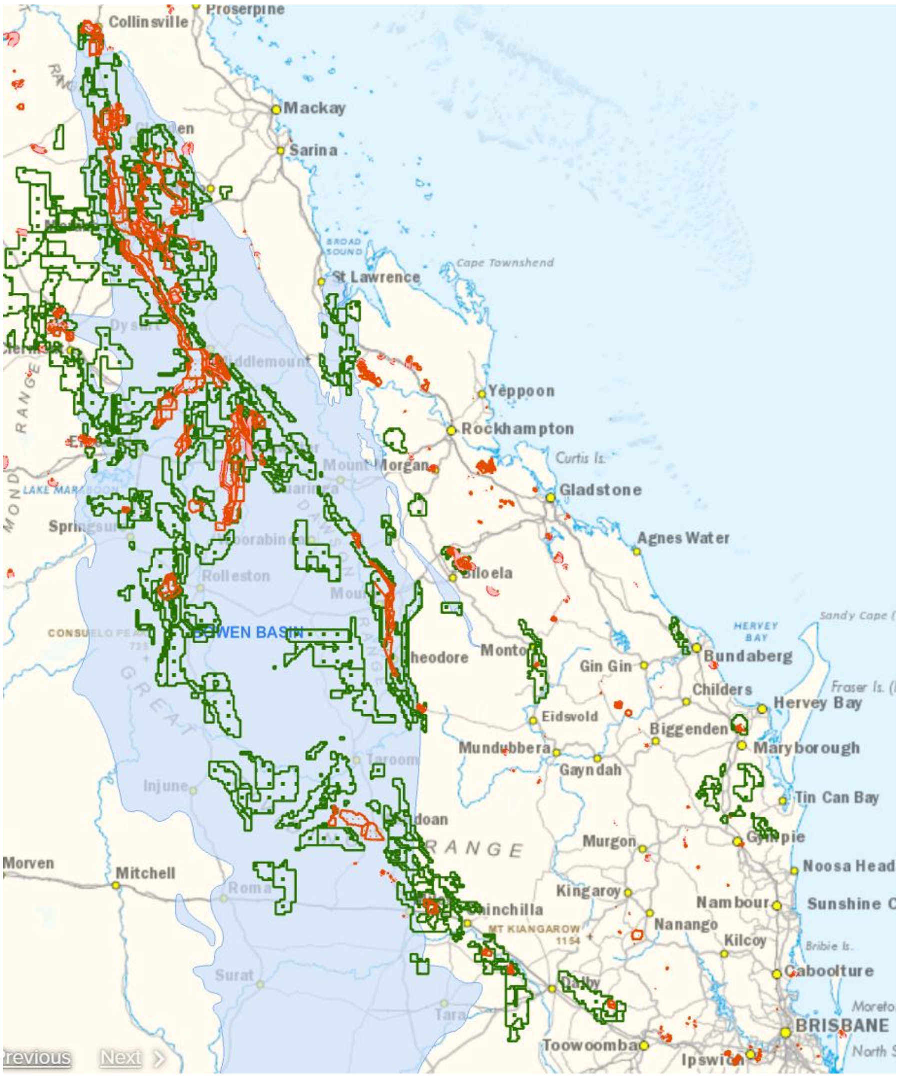


Figure 1. Area of Queensland's Bowen Basin (blue) covered by granted coal mining lease (red) and exploratory license (green) (Source: GeoResGlobe).

Of relevance for the livestock industry is that approximate 90% of land within this region is historically classified as having an agricultural land class of > C1 and was used for the grazing of native pastures (Evans *et al.*, 2015). Figure 2 illustrates this with reference to the mining region between Middlemount and Blackwater.

[20] A granted ML does authorise the mining company to undertake exploratory exercises on land for which it has not yet received surface rights.

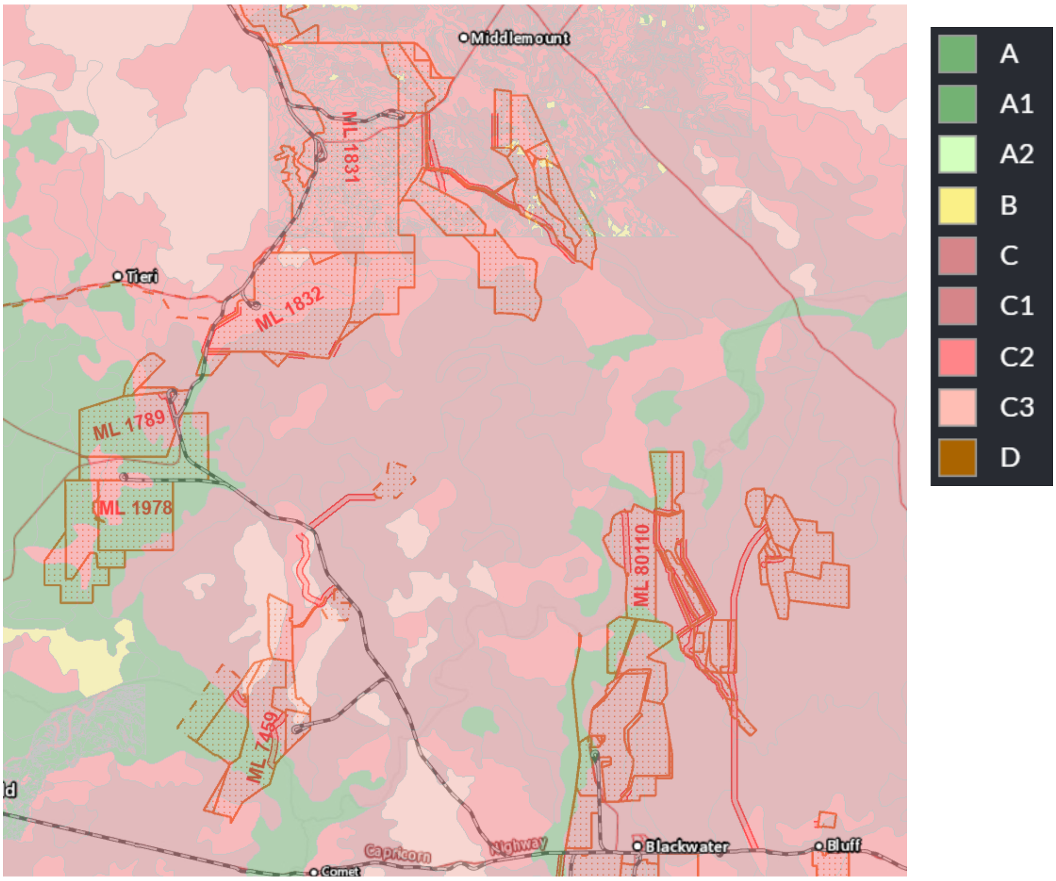


Figure 2: Map indicating that nearly all land within granted mining leases (areas encircled by red lines) between Middlemount and Blackwater was historically classified as Agricultural Land Class C1 or greater (Source: Queensland Globe 2021).

Though limited grazing activities may be conducted on land rehabilitated for this PMLU to demonstrate it meets completion criteria for relinquishment, a survey of mining companies partnering this project indicates that it is common for mining operations to exclude livestock from the area for which surface rights are granted.[21] Surface rights have been granted for 546,070 hectares under ML, representing a potential opportunity cost of approximately $59.5 million/year to the livestock industry if one assumes an annualised value of grazing land of approximately $109/ha year^{-1} for this region (De Valck *et al*., 2021).[22]

ML land comprises both undisturbed and disturbed areas. DES reported that coal mining operations had disturbed 142,965 hectares (mining and exploratory activities) in Queensland by December 2019, most of which occurred within the Bowen Basin (DES, 2020). The area of this land that will be rehabilitated for grazing as a PMLU, however, remains uncertain because until recently the Queensland Government did not keep such a register (Fogarty *et al.,* 2019). An amendment to the *Environmental Protection Act 1994 (EPA 1994*; November

[21] Rolfe *et al* (2018) refers to a period of "active management and monitoring" within the mine closure process, during which the rehabilitation process focuses on vegetation establishment, monitoring for maintenance requirements (e.g. erosion, re-planting of trees and pasture), and grazing trials that demonstrate the achievement of closure criteria.

[22] Though it seems clear that some mining companies do provide grazing access to land for which they own the surface rights, it has not been possible to establish the area to which this applies. This project assumes that very little consistent commercial livestock production occurs on this area.

2019) requires mining companies to develop Progressive Rehabilitation and Closure Plans (PRCP) that must, among other things, identify the maximum surface area they will disturb and a schematic representation of the designated PMLU areas. Since the process of developing PRCP will take many years, this information is unavailable at the present time.

Without a register that anticipates the area of grazing land that will be disturbed, this project assumes that the area currently disturbed by coal mining activities within Queensland (i.e., 142,965 ha) will continue to increase at a rate of 3,652 ha year^{-1}.[23]. If coal mining continues to disturb land at this rate, it will disturb 256,177 hectares by 2050, most of which will occur within the Bowen Basin. While there seems to be a public perception that most of this land will be rehabilitated for grazing purposes, one mining company interviewed within this project anticipates that between 50-70% of the area it disturbs with open cut extraction methods will be rehabilitated for alternative PLMU that have lower residual risks. For example, they indicate that the most likely PLMU will be native woodlands from which livestock production is excluded.

Mining company partners for this project explain that their industry needs to address the following three shortcomings if they are to rehabilitate as much land for a grazing PMLU as possible:

A. They lack livestock industry supported and scientifically validated completion criteria for grazing PMLU (Cox *et al*., 2021). Current criteria used for the Bowen Basin are determined from ungrazed rehabilitated pastures and focus on groundcover, slope, and growth media properties (Grigg *et al*., 2001). The mining partners suggest that mutually acceptable completion criteria that support viable livestock production on a range of sloped landforms (e.g. grazing days/100mm rain/hectare year^{-1} relative to slope and spoil type; optimal canopy cover for supporting production) would provide greater confidence of land offtake for this PMLU (Cox *et al*., 2021).
B. The development of design principles that guide the creation of fit-for-purpose grazing PMLU landforms in the Bowen Basin (Loch 2010). Current sustainable landform design guidelines do not prescribe design principles for the creation of functional grazing PMLU landforms and Cox *et al* (2021) observe that many landforms created for pasture establishment are less than ideal for this PMLU. Mining company partners suggest that there is a need to collaborate with the livestock industry to define design principles for creating landforms that support the achievement of viable and productive grazing PMLU.
C. The development and validation of an adaptable grazing system for achieving viable and productive grazing PMLU on sloped landforms. The use of sub-optimal overburden materials to cover sloped landforms where topsoil is unavailable may not accommodate conventional grazing methods. The project's mining partners regard the development of a grazing system that prescribes the management of a range of slopes and spoil types assist in increasing the area rehabilitated for this PMLU.

[23] This rate derives from an assumption that coal mining accounts for 65% of the 5,619 hectares disturbed by mining activities each year (EPA 2007; Rolfe *et al*., 2018). The project has attempted to obtain more recent estimates for the rate of disturbance. DES, however, confirmed that 2007 represents the most recent estimate for the rate of disturbance by mining activities. *DES, Coal Business Centre*, Email received 4th April 2022. As such, the estimate of an annual disturbance rate of 3,652 hectares may be significantly different from the actual rate.

3.1.1.2 Grazing land held adjacent to ML areas

In addition to land held under ML, mining companies own or lease significant areas of grazing land adjacent to ML areas through a common practice of acquiring or leasing rural properties partially overlapped by ML boundaries.[24] For example, in Figure 3 the boundary (red line) of mining lease ML5656 cuts across several individual freehold properties called Narweena. This project assumes that the company operating this ML will acquire each of the properties called Narweena within this example. Though larger mining companies tend to practice this approach to property acquisition, it does not always occur. As such, this assumption most likely leads to an over-estimation of the non-ML area owned or managed by mining companies.[25]

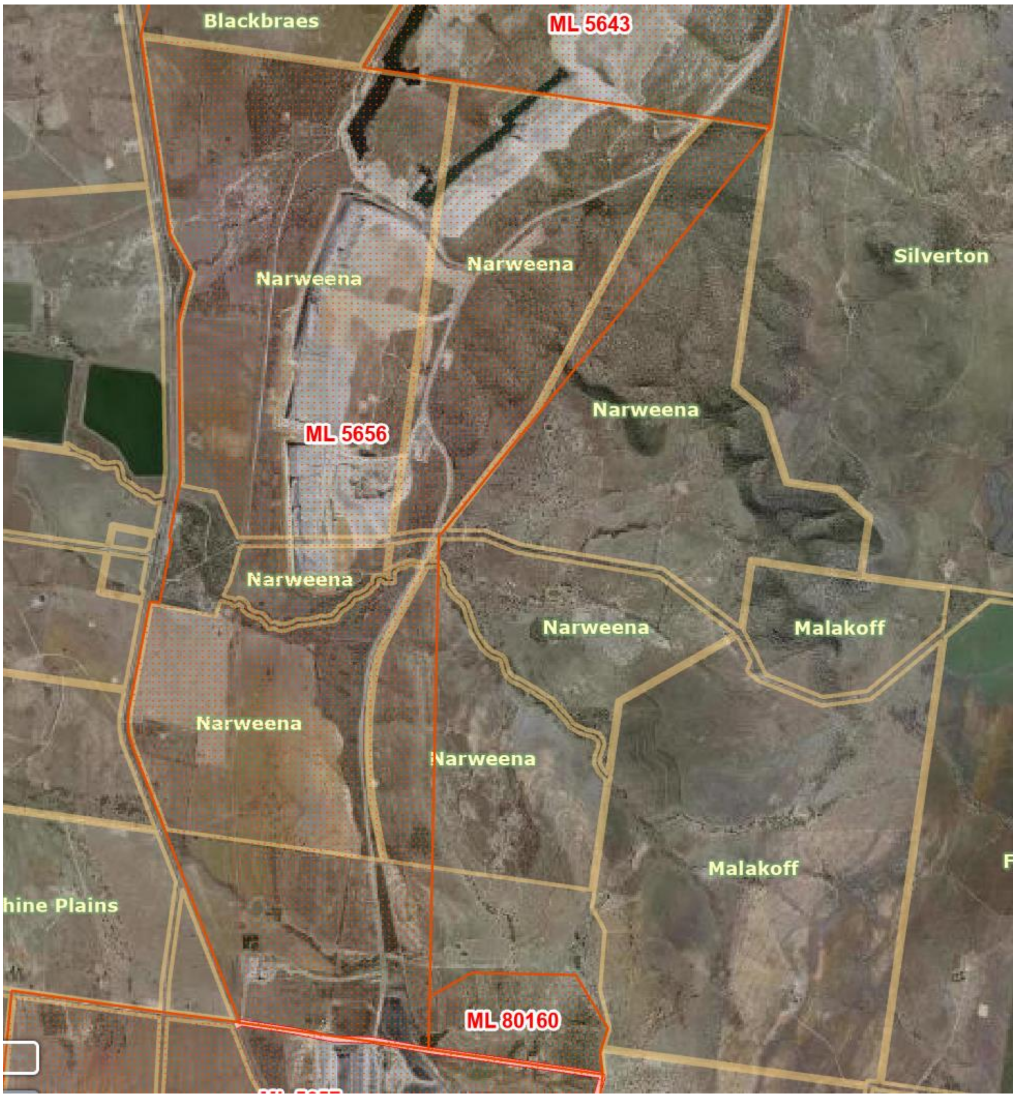


Figure 3: The relationship between mining lease and freehold land. The red shaded areas demarcate granted mining leases. The brown lines demarcate freehold properties (e.g. Narweena) (Source: GeoResGlobe).

[24] Though mining companies are not obliged to purchase properties that overlap with ML areas, the mining companies partnering this project said that this was regarded as best practice.

[25] It may also represent an underestimation. For example, this project has observed that one of the partnering companies owns freehold land that does not adjoin ML areas. This type of land has not been included in the calculations for land ownership by mining companies.

Non-ML land owned or managed by coal mining companies is already used for livestock production. Except for one mining company which operates its own pastoral company, the mining companies partnering with this project typically agist this land to previous landholders or to graziers operating on adjacent properties. The project's mining partners were not able to share the management requirements included within agistment agreements because they are commercial-in-confidence. They indicated, however, that the requirements are high level statements confined to expectations that grazing is "best practice." The mining companies who agist land observe that graziers do not intentionally attempt to improve land condition or achieve carbon sequestration and biodiversity goals.

3.1.1.3 Availability of mining owned or managed land post-relinquishment

The project determined the area of mining owned or managed land within the Bowen Basin that would become available for livestock production through the process of mine closure and land relinquishment by making the following assumptions:

A. The industry will disturb 256,177 hectares through mining and exploration activities.[26]
B. Mining companies acquire or lease land packages partially overlapping ML boundaries.
C. Approximately 90% of the undisturbed land owned by mining companies was historically used for extensive livestock production.

The estimated land area and types currently owned or managed by mining companies that will become available to the livestock industry through mine closure process within the Bowen Basin are presented within Table 1.

Table 1: Area of land owned or leased by mining companies in Queensland's Bowen Basin

Land category	Hectares
Total land owned/managed	760,627
Granted ML	557,696
Granted Surface Area	546,070
Area adjacent to ML areas	202,931
Anticipated ML area disturbed by 2050 (mining & exploration)	256,177

Since MLs are granted with an expiry date, it is possible to anticipate the rate at which this land *may* be relinquished. This statement requires at least two qualifications. First, a mining company is not obliged to sell or relinquish land that it holds under an expired ML. As will be discussed below, the legislative requirement for a mining company to obtain certification that land has been rehabilitated may delay its relinquishment beyond an ML expiry date. At present, DES has certified less than 1% of granted mining land as rehabilitated (i.e. < 5000 hectares).[27] Second, a mining company may apply for an ML's renewal. Figure 4 reflects that almost 50,000 hectares of ML land was due to expire in 2020. This land, however, remains under active ML pending the outcome of renewal applications. Therefore, though it seems unlikely land will become available as represented

[26] It is not possible to calculate the proportion of ML areas that will be disturbed because the rate at which the latter will increase remains unknown. The area of granted ML in the Bowen Basin has increased from 446,726 hectares in 2013 (Erksine and Fletcher, 2013) to 557,696 hectares in 2021, an average rate of expansion of 13,871 hectares year^{-1}. At this rate and without the relinquishment of MLs, the total granted ML area could increase to 987,697 hectares, 26% of which would have been disturbed.
[27] DES, Business Centre Coal, Email received 4th April 2022.

in Figure 4, ML expiry dates provide the most accurate means for anticipating the rate at which land will become available to the livestock industry. This project assumes that the land owned by mining companies that sits adjacent to ML areas will become available at the same rate.

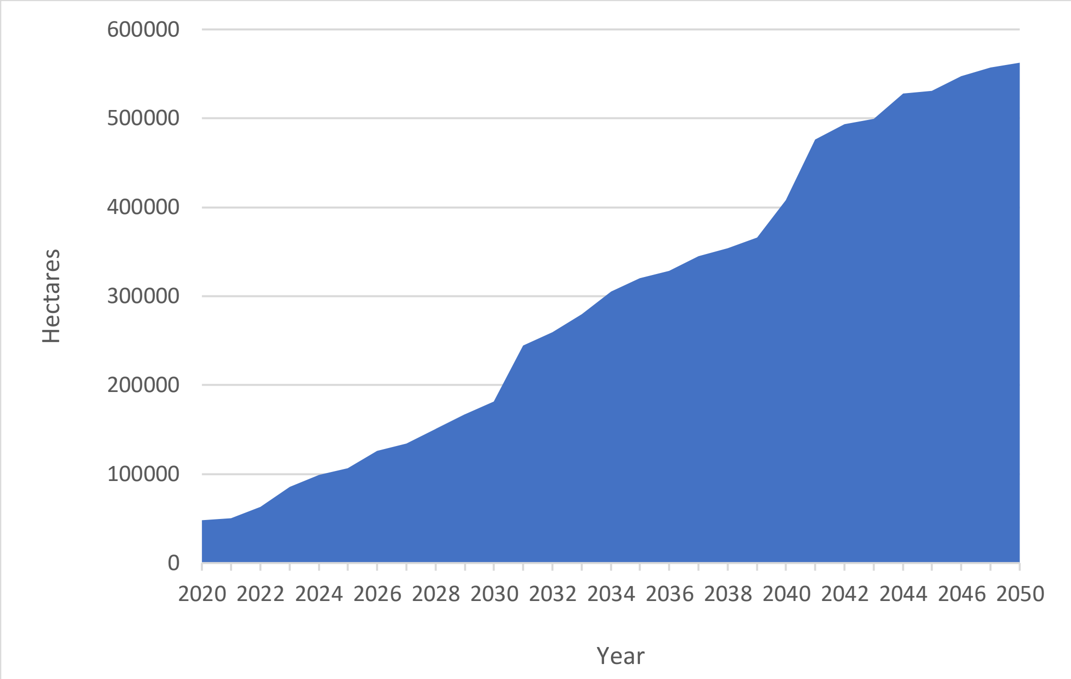


Figure 4: Cumulative area of expiring granted coal ML (ha) within Queensland's Bowen Basin

As mines close, they will relinquish ML land as packages of undisturbed grazing and rehabilitated land types. Land rehabilitated for grazing purposes will constitute just one such rehabilitated land type. Other types will comprise final water-filled voids, forested and rock-armoured slopes unsuitable for grazing, and in some cases contaminated areas.

An example of the parcellated layout of rehabilitated grazing land within a larger undisturbed grazing land package is illustrated in Figure 5.

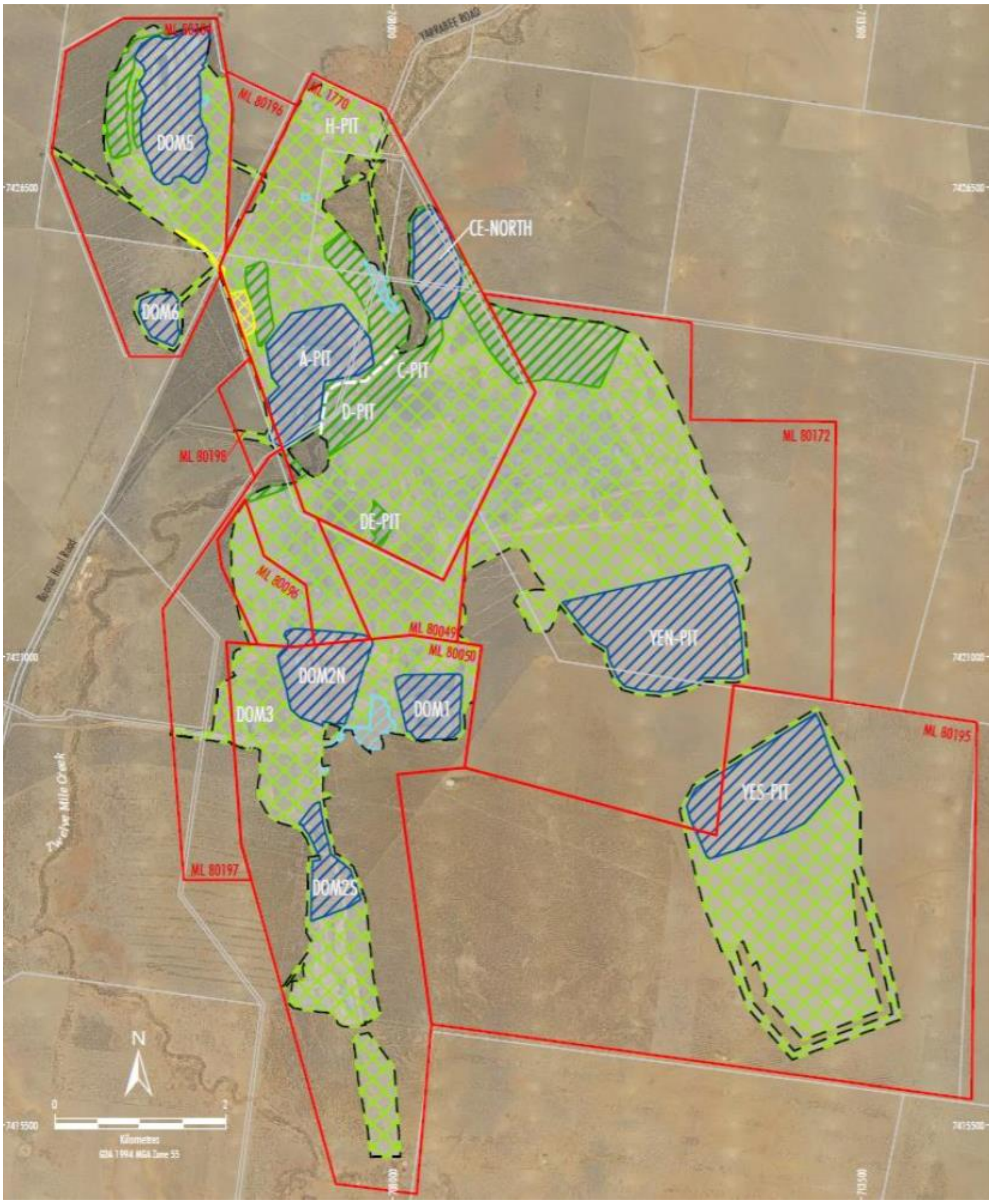


Figure 5: Schematic representation of post-mining land use areas at the Yarrabee Coal Mine, Queensland (Source: Environmental authority EPML00844613). Final land use areas: Native vegetation (Dark green); Low intensity grazing (Light green), Water storage (light blue). Non-use management area: Residual void (Dark Blue). Red lines represent granted ML boundaries. Black lines demarcate the extent of surface rights.

The schematic representation of PMLU areas for the Yarrabee Coal Mine (Figure 5) serves to illustrate the unique challenges relinquished mining land packages will pose for future landowners. In addition to acquiring undisturbed historical grazing land, the new owners will need to manage the grazing of unique sloped rehabilitated landforms abutting other rehabilitated areas that will remain off-limits for livestock production. The latter areas are referred to "special management areas" that cannot be completely rehabilitated and require long term management to mitigate the inherent risks they post for people and the environment. The management of these areas upon mine closure will transfer to the Queensland Government rather than new landholders.[28]

3.1.1.4 Summary of the quantum of mining land types in the Bowen Basin and their availability for livestock production

The project has made the following estimates for mining land types and their relative availability for livestock production in the Bowen Basin:

- Coal mining companies own or manage up to a total of 760,627 ha comprising ML land (557,696 ha) and 202,931 ha of land that sits adjacent to ML areas.
- Mining companies largely exclude livestock from 546,070ha for which they have granted surface rights within ML areas. Access to these areas is constrained by (a) stringent health and safety requirements within site management plans, (b) the large operational space required for mining activities, (c) the proportion of land disturbed or scheduled for disturbance, (d) the proportion of disturbed land already rehabilitated for grazing purposes, and (e) the proportion rehabilitated for non-grazing PMLU (e.g. rock armoured slopes, forested areas, water filled voids).
- 256,177 hectares of ML land will be disturbed by coal mining and exploration activities and require rehabilitation by mining activities by 2050. The proportion of this area disturbed by open cut coal mining is not specified in data released by DES.
- Some mining companies anticipate that 50-70% of land disturbed by open cut mining will be rehabilitated for alternative PMLU that exclude grazing because they lack (a) scientifically and livestock industry supported completion criteria for grazing PMLU, (b) design principles for creating grazing PMLU landforms, and (c) a grazing system for achieving grazing PMLU completion criteria on sloped landforms.
- The 557,696 ha of ML land and a further 202,931 ha of adjacent undisturbed land may become available for relinquishment as MLs expire over the next 30-years. Nevertheless, this time will lengthen should mining companies obtain ML extensions or take longer than expected to obtain certification that land has been rehabilitated for relinquishment.
- Land packages that become available through the mine closure process will comprise rehabilitated landforms and livestock exclusion areas (Special Management Areas) parcellated within larger undisturbed grazing areas.

The next section considers the biophysical characteristics and limitations of these mining land types for livestock production and assesses the opportunity they present the livestock industry pre- and post-mine closure.

3.1.2 Biophysical characteristics and limitations of mining owned or managed land for livestock production

Mining companies own or manage two types of land that have relevance for livestock production in Queensland's Bowen Basin, namely (a) ML land disturbed by mining activities that has the potential for rehabilitation as grazing PMLU (b) undisturbed historically degraded grazing land within or adjacent to ML areas. This section discusses the

[28] Queensland Resources Council (2017), Rehabilitation and Relinquishment [online] Available at: https://www.qrc.org.au/policies/rehabilitation/ [Accessed 3rd February 2022].

biophysical characteristics of these respective land types and the opportunities and challenges they present for livestock production.

3.1.2.1 Undisturbed mining land and the opportunity it affords the livestock industry

The *undisturbed land* owned or managed by mining companies that has relevance for livestock production comprises two broad land types relevant for livestock production. First, approximately 202,931 hectares sits adjacent to ML areas and is not scheduled for disturbance by mining activities.[29] The mining companies partnering with the present project emphasise that any need for remediation of this land derives from its historical degradation by sub-optimal farming practices. As such, the challenges for improving the environmental and production outcomes from this type of land is no different from those that apply to degraded grazing land elsewhere in the Bowen Basin.

Second, most ML land will remain undisturbed at the time of mine closure. Unfortunately, a public register for the size of this area does not exist. Historically, mining companies were not required to estimate the area of ML land they anticipated would remain undisturbed at mine closure.[30] Given that coal mining companies self-report that they had disturbed 142,965 hectares (mining and exploration activities) in Queensland by December 2019, most of which can be assumed to have occurred within the Bowen Basin, it seems reasonable to assume that a large proportion of the 557,696 hectares of current ML area remains undisturbed and suitable for grazing purposes.[31] Undisturbed land within ML boundaries may not become reliably availably for livestock production until after mine closure. These areas will present the same challenges for remediation as other historically degraded grazing land types in the Bowen Basin.

The project's mining partners were interviewed to understand their current management and strategic objectives for their undisturbed land. Their responses to a questionnaire (Appendix 8.2) are summarised in Table 2.

[29] Nevertheless, should exploratory activities reveal underlying coal measures a mining company may later apply for an ML over these areas.

[30] New Progressive Rehabilitation Closure Plan (PRCP) legislation requires companies to disclose this information over the coming years. Queensland Government, *Guideline: Progressive Rehabilitation and Closure Plans (PRC)* (DES, 2018)

[31] It needs to be kept in mind that the 142,965 hectares of land already disturbed by coal mining extends beyond ML areas to include land disturbed by exploration activities.

Table 2: Project mining company responses to survey of management practices for undisturbed grazing land under their ownership or management

Question or topic	Mining company partner		
	Company A	Company B	Company C
Are undisturbed areas within ML areas grazed?	No	Grazing is excluded from areas where they have surface rights for land disturbance	Yes, removed from the vicinity of active mining operations
Who manages undisturbed off-lease grazing land?	Company A's pastoral company	Lessees	Lessees
How is undisturbed grazing land managed adjacent to ML areas?	Maintain > 1200kg DM/ha pre-growing season	Maintain adequate groundcover and manage notifiable weed incursions	Maintain adequate ground cover.
How are trees managed?	< 5% tree cover for shelter	No policy	No policy
How are riparian zones managed?	Fenced depending on soil type	No policy	No policy
What grazing system is used?	Continuous with a 12 week; complete rest during wet season/3-4 years	Continuous grazing	Continuous grazing
Soil carbon measurements?	No	No	No
Carbon sequestration objectives?	No	No	No
Biodiversity measurements?	No	No	No
Biodiversity targets?	No	No	No

The following observations from Table 2 have relevance for this project. First, the mining industry may largely exclude livestock production from undisturbed grazing land held within ML areas for which they have granted surface rights (546,070 hectares). Though the Mine and Quarrying Safety and Health Act (1999; "the Act") does not preclude the presence of livestock within MLs, grazing activities may be excluded on the basis of (a) the legislative requirements for safety and health on mine sites; (b) site-specific health and management systems; and (c) practical needs for keeping non-mining and mining activities separated to reduce risk.[32] The quantum of this land that will become available for livestock production will depend on the extent of future disturbance and the proportion of disturbed land rehabilitated for grazing PMLU.

Second, the mining partners of this project indicated that their present strategic objectives for livestock production on their accessible undisturbed grazing land (predominantly adjacent to ML areas) is limited to the maintenance of groundcover and weed control. A reluctance of current land managers to invest in the implementation of practices that improve land condition and environmental conditions seems an understandable consequence of agistment arrangements. Why would a grazier invest in the water and fencing infrastructure required to support alternative remedial practices? Conversely, this observation presents an opportunity to incentivise the implementation of practices that remediate this land by rewarding lessees for implementing practices that achieve carbon sequestration and biodiversity targets that benefit mining companies.

The third observation one may make from Table 2 is that these mining companies have not yet developed strategic environmental, carbon sequestration, or production objectives for undisturbed areas that sit adjacent to mine leases. This represents an opportunity for the livestock industry to partner with mining companies in determining achievable objectives using livestock production.

Fourth, there is no evidence that the companies have proactively encouraged the strategic use of trees on this land. Company A estimates that < 5% of its land is covered by tree canopy. It seems likely that significant carbon sequestration, biodiversity, and environmental services benefits can be achieved by the strategic management of tree regrowth on this land.

Fifth, continuous grazing practices are implemented on undisturbed areas. The most granular description for grazing practices was provided for Company A's owned or managed land. Its pastoral company continuously grazes land except a 12 week rest each year, and a full growing season rest every 3-4 years. Except for Company A, the *status quo* for the grazing management of undisturbed land seems to lack intentionality to increase productivity, carbon sequestration, and biodiversity.

Finally, the companies were unable to provide soil or biodiversity records for undisturbed areas. They indicated, however, that the land they acquire is typically degraded by historically suboptimal grazing management.

3.1.2.1.1 Opportunities undisturbed land affords the livestock industry

The opportunities that the biophysical context of undisturbed mining land affords the livestock industry relate primarily to the implementation of:

A. Grazing practices that remediate historically degraded land to support sustainable and profitable beef production.

[32] The Act requires Queensland mine sites to operate under the authority of a Site Senior Executive (SSE) who is responsible for implementing a site health and management system. The SSE carries significant personal liabilities and financial penalties in the event where preventable accidents occur. It is understandable that an SSE may choose to reduce risk by excluding livestock production from within ML boundaries.

B. Practices that facilitate the achievement of mining industry targets for offsetting operational carbon emissions and net zero loss of biodiversity.

Though it seems unlikely that undisturbed land within ML areas will become available for livestock production before mine closure, about 202,931 hectares of non-ML represents a significantly immediate opportunity for the livestock industry to service the delivery of carbon sequestration while remediating it for productive, profitable, and sustainable beef production. All three partnering mining companies share a common commitment to exploring opportunities for achieving net zero operational greenhouse gas emissions by or before 2050, though it seems likely that this commitment is shared by all mining companies operating within Queensland's Bowen Basin.[33]

There is also an opportunity for the livestock industry to service the improvement of biodiversity on the undisturbed land that sits adjacent to ML areas.[34] The Queensland Government requires mining companies to (a) account for any loss or disturbance of biodiversity through their activities and (b) offset or rehabilitate these losses (EPA 1994). At least two of the three partnering companies are committed to delivering no net loss or a net positive impact on biodiversity.[35] Though mining companies have developed significant expertise in the development and management of biodiversity offsets and the rehabilitation of areas for biodiversity enrichment, this project did not find evidence that they are intentionally attempting to achieve gains in biodiversity on land they own adjacent to ML areas.

This project anticipates that the undisturbed land adjacent to ML areas offers the following specific opportunities for the livestock industry:

A. The establishment of a silvopastoral system that services mining company commitments for achieving net zero operational carbon emissions and biodiversity loss.
B. The implementation of grazing management systems that support the emergence and maintenance of biodiverse pasture species and optimise carbon sequestration through the managed regrowth of tree belts.
C. A resource for supporting the sustainable grazing management of adjacent rehabilitated land parcels as these become relinquished.
D. Remediation of land for supporting profitable and sustainable beef production post land relinquishment by mining companies.

3.1.2.2 Biophysical context of mining land rehabilitated for grazing purposes

The development of a pathway for remediating mining land for productive, profitable, and sustainable beef production is important because the post-mining landscape will be characterised by areas of rehabilitated landforms parcellated within larger undisturbed

[33] BHP: Pathways to Net Zero (P2NZ); Glencore, *Pathway to Net Zero* (Climate Report, 2020); Anglo American, Climate Change Report 2021.
[34] The biodiversity values of remnant vegetation within undisturbed ML areas are generally in a much better condition than adjacent grazing properties (John Rolfe. Pers. Comm).
[35] BHP and Anglo American employ a mitigation hierarchy (i.e. avoid, minimise, rehabilitate, compensatory actions for any residual impacts) to achieve a minimum of net zero biodiversity loss across their respective operations. See BHP, ESG Roundtable (September 2021); Anglo American, Our Sustainability Plan (2021).

land packages. On the one hand, it seems necessary to develop a model whereby post-mining land users can integrate the management and maintenance of these landforms within their normal grazing operations. On the other hand, the pathway needs to provide a method by which these graziers can partner with the mining industry to implement practices that achieve completion criteria for viable and productive grazing PMLU on sloped rehabilitated landforms.

Coal mining activities cause two distinct types of land disturbance in Queensland's Bowen Basin that may challenge its rehabilitation for grazing purposes. The first and most destructive type of disturbance is caused by open cut mining which requires the complete reconstruction and rehabilitation of landforms. This method is used in 87% of coal mines (De Valck *et al.*, 2021) and this report focusses on the development of a silvopastoral model for addressing this kind of disturbance.

The second type of mining disturbance relates to the subsidence of grazing land and the associated hydrological changes caused by underground longwall mining. The impact of underground mining on the rolling downs type landscapes of the Bowen Basin is relatively minor compared with that of open cut mining (Lechner *et al.,* 2016). Since this kind of disturbance is not the core focus of the silvopastoral approach developed within this report, an overview of this mining method and its significance for grazing land is provided in Appendix 8.3.

Before considering a range of livestock management practices that may enhance the environmental and production outcomes for grazing PMLU, it seems necessary to provide an overview of the biophysical context of open cut coal mining disturbed land, the conventional practices used for rehabilitating this land for grazing purposes, and the historical outcomes of these practices for the livestock industry. A consideration of these topics will inform a discussion of the opportunities for the livestock industry to service some of the mining industry's rehabilitation requirements.

3.1.2.2.1 Land disturbed by open cut coal mining and its rehabilitation for a grazing PLMU

Open cut coal mining causes the most drastic disturbance to land and requires the most significant rehabilitation investment for achieving PMLU completion criteria. To provide some context for understanding this mining method and the rehabilitation process, Figures 6 and 7 present satellite images of mining lease ML 5657 which is situated within the Dawson mine near Moura, Central Queensland.

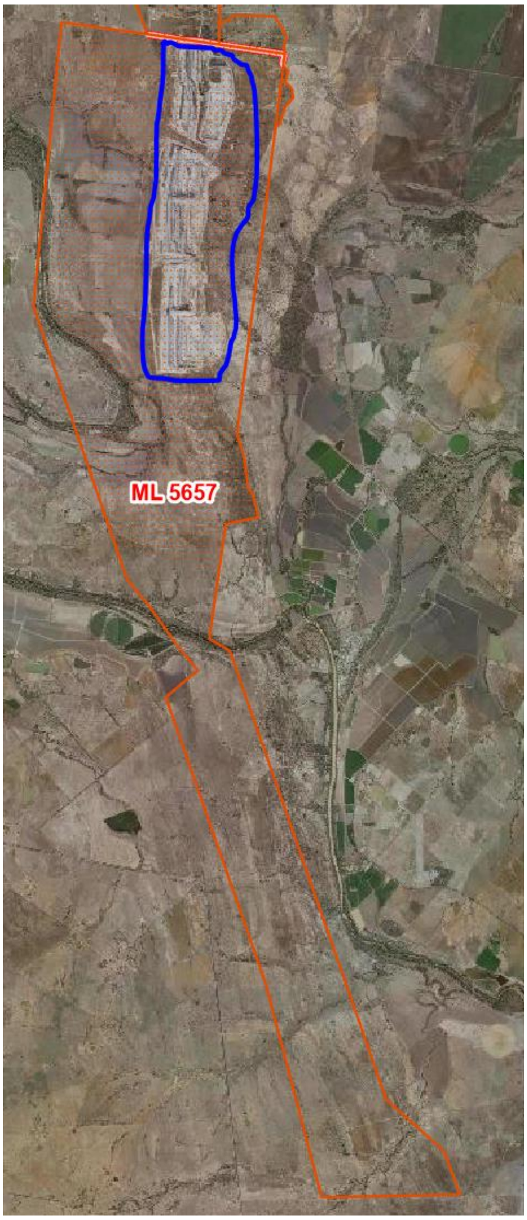


Figure 6. ML 5657 near Moura, Central Queensland. The red line represents the ML boundary. The area of ML 5657 disturbed by mining activities is encircled by the blue line (GeoResGlobe)

Figure 6 illustrates the typical layout and context of land disturbed by this kind of mining in the Bowen Basin. The mining disturbed area that requires rehabilitation (blue outline) is parcellated within a much larger area of undisturbed, albeit historically degraded grazing land held under mining tenure. For example, though ML 5657 covers 8,796 hectares, approximately 1725 hectares are mining disturbed and will require rehabilitation.[36]

The typical layout and operational elements of an open cut coal mine are illustrated in Figure 7 with reference to the same granted mining lease (ML 5657).

[36] The disturbed area has been estimated using GeoResGlobe (21st January 2022).

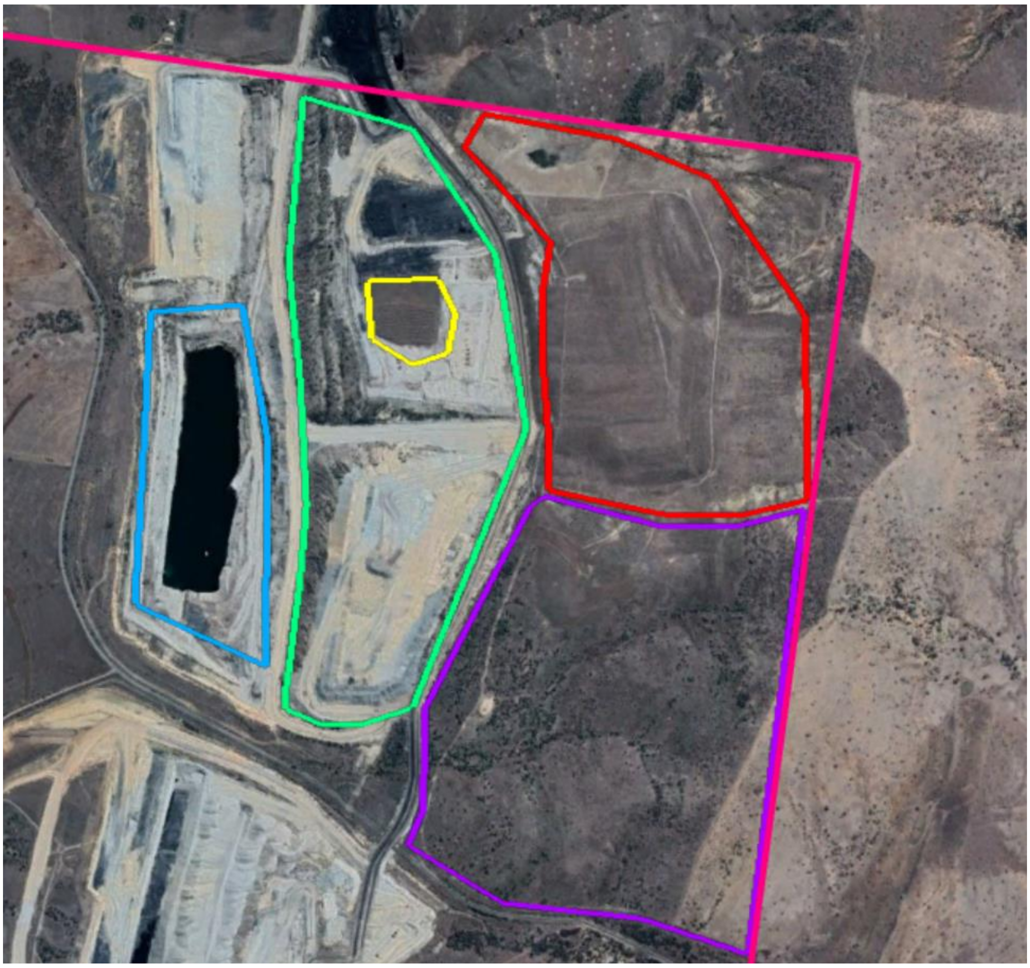


Figure 7: Dawson Mine (ML 5657), near Moura, (Red area: disturbed land rehabilitated for grazing purposes; Blue area: water filled void; Green area: spoil dumps; Yellow area: topsoil stockpile; Purple area: undisturbed grazing land; Pink line: ML 5657 boundary) (Google Earth Pro: 14/09/2018)

Open cut coal mining operations within the Bowen Basin typically progress excavations in pursuit of coal seams that gradually deepen. Prior to excavating materials overlying the coal seam, topsoil is stripped to the depth of the soil profile's A horizon (c. 20-30cm) and either immediately spread where land is being progressively rehabilitated or, where this is not an option, stockpiled for subsequent spreading on landforms shaped from spoil materials (Yellow area in Figure 7; Goh *et al*., 1998). Mining operations attempt to maintain the integrity of the topsoil by stockpiling it in a way that avoids compaction, weed infestation, water logging, and erosion.[37] Nevertheless, the loss of the natural structure and biome of the topsoil through the stripping and stockpiling process lessens its effectiveness for establishing a feedbase during the subsequent rehabilitation process.

[37] For example, the partnering mines to this project instruct operators to (a) avoid double handling and directly place topsoil on areas for rehabilitation wherever possible; (b) avoid stockpiling for more than 12 months; (c) practice weed control on stockpiles to minimise the accumulation of a weed seedbank; (d) maximise surface area to volume ratio of stockpiles; (e) keep stockpiles less than 3-4 metres high to avoid anaerobic conditions; and (f) seed piles with grass species endemic to the area and Rhodes Grass (*Chloris gayana*)

After topsoil stripping, the materials overlying the coal seam are removed and placed in spoil dumps behind excavations (Green area in Figure 7). The significant depth of excavation, the limited area for dumping, and higher volume of loosened overburden than its undisturbed state result in the creation of elevated sloped dumps. Mining operations aim to rehabilitate these spoil dumps progressively behind continuing excavations (Red area in Figure 7). The dumps are regraded to achieve appropriately sloped land for the target PMLU, though the final landforms will remain of greater elevation and steeper slope than the surrounding natural landscape (Emmerton *et al*., 2018).[38]As such, areas for rehabilitation are often characterised by long sloped areas (Figure 8).

Figure 8. Sloped rehabilitated landform, Bowen Basin, Queensland

The larger surface area created by the elevated final landforms is a contributing factor to the topsoil deficit that challenges the rehabilitation of land for grazing PMLU. Where stockpiled topsoil is unavailable for spreading over spoil, mining operations select the most appropriate spoil-material for covering landforms to minimise the erosion risks and establish vegetation. Within the Bowen Basin, spoil materials are primarily generated from the excavation of three geological layers overlying coal seams, namely the Quaternary, Tertiary, and Permian (Figure 9). Within these layers, Tertiary sediments are commonly sodic and dispersive whereas Permian materials are (mostly) more stable (Gunn *et al*., 1967). Therefore, where a topsoil deficit prevails mining operations prioritise the burial of these Tertiary-derived materials under Permian spoil (Dale *et al*., 2018). Though mines undertake to separate spoil from different geological layers to achieve this outcome, in practice these layers can become mixed (Spain and Hollingsworth, 2016), making it difficult to avoid covering final landforms with sodic and dispersive spoils.

[38] Naturally occurring landforms within the Bowen Basin often have slopes of less than 3% (Emerton *et al*., 2018), significantly less than slopes of up to 20% of landforms rehabilitated for grazing purposes on some mine sites (Mining company partners, pers. Comm).

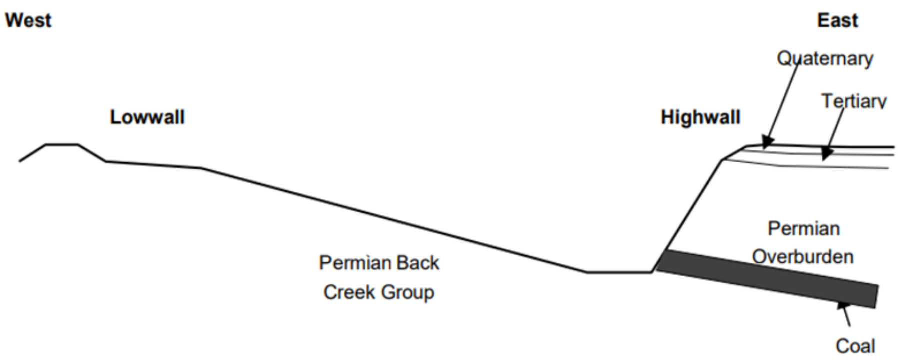


Figure 9. Schematic Cross-Section of Open Cut Coal Mine in the Bowen Basin, Queensland

The use of spoil for covering a landform presents problems for its rehabilitation to support livestock production as a post-mining land use. Their low organic (OM) matter content reduces their capacity to retain moisture and nutrients and they lack a living biome responsible for providing other environmental services within natural topsoil.

In addition to the limitations that characterise all spoil materials, sodic and dispersive spoils present additional challenges for the rehabilitation process by making artificial sloped landforms highly vulnerable to erosive forces. Within sodic spoils, sodium ions take up most cation exchange sites on clay particles, and this may cause spoils to become dispersive when wet. Though contingent upon other chemical and physical variables present (e.g., clay content, nature of clay, pH), the relatively large electron shell of the positively charged sodium ion results in these particles repelling one another when the soil becomes wet, leading to the dispersion of clay particles. Highly saline spoils are not always dispersive, however, because as the ionic concentration of the soil solution increases the repulsive forces between clay particles diminish (Dale *et al*., 2018). As such, a ratio between a spoil's exchangeable sodium percentage (ESP) and electrical conductivity (EC) is regularly used to assess its risk of dispersing in contact with water. The ESP is the ratio of Na+ to the spoil's Cation Exchange Capacity (CEC) and the EC measures concentration of soluble ions. Soils with an ESP of greater than 6 are regarded as sodic and above 15 as extremely sodic (Northcote and Skeen, 1972). The relationship between a spoil's ESP/EC ratio and its risk of dispersion/erosion can be set out in Table 3 (Dale *et al*., 2018):

Table 3. The relationship between ESP/EC and a spoil's risk of dispersion

ESP (%)/EC (dS/m)	Risk of dispersion
0-5	Low
5-12	Medium
>12	High

The risk of erosion posed by saline and sodic spoils is exacerbated by their provision of a poor soil environment for establishing vegetation (Spain and Hollingsworth, 2016). Saline and sodic spoils interfere with germination (Bewley and Black 1978), inhibiting growth by causing osmotic stress, and may adversely influence microbial activity (Spain and Hollingsworth, 2016). The poor vegetative ground cover outcomes on these spoils further increase the risk of erosion.

In addition to the challenges posed by a topsoil deficit, open cut coal MLs invariably contain areas that cannot be rehabilitated for grazing as a post-mining land use. For example, mining operations most often terminate at final deep excavations which, if not backfilled will remain as legacy voids. Areas such as water filled voids, contaminated land, and steep rock-armoured or forested spoil covered landforms will be excluded from grazing activities when land is finally relinquished during the mine closure process.

3.1.2.2.2 Addressing the challenges for rehabilitating reconstructed landforms for grazing PMLU

The foregoing overview of the open cut coal mining and rehabilitation process reveals two primary biophysical challenges for achieving a grazing PMLU:

A. Sub-optimal spoil coverings for grazing purposes

A 30-50% topsoil deficit threatens to produce less than satisfactory outcomes for the livestock industry from rehabilitated sloped land where open cut coal mining has occurred (Lamb *et al*., 2015). This deficit relative to rehabilitation requirements can necessitate the establishment of vegetation directly into what are often sodic and dispersive spoil materials (Grigg *et al*., 2000).[39] Where topsoil is available, the incorporation of subsoil during the original topsoil stripping process and long-term stockpiling may severely impair its quality (Lamb *et al*., 2015). These factors reduce the topsoil's OM content, important for soil structure, nutrient availability, and water retention (Grigg *et al*., 2000). Furthermore, the stockpiling of stripped topsoil destroys its natural biome, reduces native seed viability, and accumulates a seedbank of weed species (Spargo and Doley, 2016).

B. Elevated sloped landforms

The significant excavation depths required for extracting coal measures and limited space for dumping overburden materials necessitates the creation of elevated dumps with steep slopes. Though the rehabilitation process regrades slopes to achieve a more functional and sustainable landform, this is a costly process and landforms often remain significantly steeper than the surrounding natural landscape. These sloped areas exacerbate the erosion risk posed by a reliance on sodic and dispersive spoil material coverings. On the one hand, the exposed elevated slopes have a lower relative humidity than surrounding areas, creating a less favourable context for establishing groundcover (Grigg *et al*., 2000; Ahirwal and Maiti 2018). On the other hand, the slopes themselves increase the likelihood of erosion via water runoff and wind exposure.

Mining companies attend to three biophysical components of a reconstructed landform to overcome or minimise these challenges for achieving completion criteria for grazing PMLU, namely landform design, the inherent chemical and physical properties of available spoil materials, and vegetative ground cover. The following briefly summarises

[39] Spoil refers to materials that once overlay coal seams extracted using open cut mining methods.

the best practice methodologies rehabilitation operations use in attending to these respective biophysical components.

A. Landform design

Spoil materials are more voluminous than their pre-excavated state, making elevated sloped landforms an inevitable feature of rehabilitated landscapes. Landform slope gradients, slope lengths, and shapes are designed to lessen the impact of water-caused erosion by managing how water enters the soil. Though contingent upon site specific physical and chemical characteristics of spoil, it seems that there is some consensus that best practice landform design for dispersive spoils seeks to achieve:

a. The regrading of spoil dumps to achieve slopes of < 12% (Grigg *et al*., 2001), though Dale *et al* (2018) report that slope gradients of < 10% may still fail via erosion for spoils in the range of 5-12 ESC/EC. To achieve a land suitability class of ≤ 3, at least one mining company partnering this project recommends slope gradient according to spoil ESP (Table 4):

Table 4. Minimum slope requirements for a range of spoil ESP

ESP	% Slope
< 6	> 8-12
> 6 < 14	> 6-10
> 14-23	> 2-4

b. Minimal slope lengths to reduce velocity of water run-off. Ideally, uninterrupted slope lengths should be no greater than 10 metres to reduce erosion below 2.5%/year and Dale *et al* (2018) indicate that spoil surface materials of 5-12 ESC/EC will potentially fail when slope lengths are 25 metres.

c. Concave shaped slopes are often preferred for mitigating the risks of erosion, though see Howard *et al* (2011) for qualifications relating to site specific physical and chemical spoil characteristics. Within their risk mitigation framework for dispersive soils, Dale *et al* (2018) propose that a concave shape removes the risk of erosion on 5-12 ESC/EC spoil slopes.

d. Rock-armoured slopes. Where high gradient slopes are unavoidable, mining operations may elect to install rock armouring. Rock is mulched to a uniform size (*c.* 50 cm) and used to cover slopes that are unsuitable for future grazing purposes.

In considering the application of a silvopastoral model for managing rehabilitated landforms, this report assumes its application to elevated landforms of minimal concave slope < 10% unless the nature of spoil covers allows for steeper slopes. It also assumes that erosion is reduced by limiting uninterrupted slope lengths to as little as < 10 metres where this is made necessary by the sodic nature of ground coverings.

It seems noteworthy that there is no evidence of scientifically informed or livestock industry supported design principles that specifically focus on supporting the achievement of viable and productive landforms. This report recommends that the livestock industry may benefit from collaborating with the mining industry to develop these principles to create functional landforms that will support grazing PMLU post mine closure

B. Amendment of spoil physical and chemical properties

To address the risk that sodic and dispersive spoils pose for erosion and feedbase establishment, the rehabilitation process incorporates calcium and/or organic matter (OM) amendments into spoil:

a. Amendment with calcium using gypsum or lime

The incorporation of a calcium source, most commonly Gypsum, reduces the dispersiveness of clay particles by (i) increasing the electrolyte concentration in soil water, thereby reducing the size of electron shells around clay particles and (ii) displacing sodium ions taking up cation exchange sites with calcium ions. Since calcium ions have a thinner electron shell, the clay particles exert less pressure on each other when wet.

Dale *et al* (2018) reported a lack of confidence among rehabilitation operations within the Bowen Basin that the use of ameliorants such as gypsum work and this same sentiment has been expressed by some mining company partners in the present project. Nevertheless, Dale *et al* (2018) suggest that less than optimal methods of incorporation may be responsible for inconsistent results. They demonstrated a negative correlation between erosion severity and cations with higher levels of ionicity (i.e., Ca+, Fe+) and silt.

This report's development of a silvopastoral model assumes that, where necessary, spoil overlaid on new landforms has been appropriately amended with a calcium source.

b. Amendment with OM

The benefits of amending dispersive spoils with OM are well-documented (Leogrande and Vitti, 2019; Fang *et al*., 2021). Amendment with OM can improve soil structure and drainage, moisture holding capacity, nutrients for plants and soil biota, and cation exchange capacity (CEC). Grigg *et al* (2006) demonstrated that the incorporation of straw mulch into sodic and dispersive spoil at a rate of 20 tonnes DM/ha increased water infiltration and reduced salinity. They reported that mulch incorporation improved water infiltration by (i) protecting the soil surface from raindrop impacts that would ordinarily cause a hard seal to form via the breakdown in surface structure and (ii) providing stable pathways for water entry into the subsoil. They indicated that the reduction in spoil salinity was achieved by the incorporated mulch improving subsoil permeability, thereby mitigating against capillary rise of salt during the drying of soils.

The use of municipal liquid biowaste OM to establish trees directly into spoil is discussed in Section 3.3.1.3.

c. Establishment of vegetative groundcover

The establishment of adequate vegetative groundcover is critical for mitigating the risk of erosion from spoil covered landforms. The required coverage for preventing erosion varies according to the slope and dispersiveness of exposed spoil. Grigg *et al* (2001) reported that the achievement and maintenance of groundcover > 70% was necessary for controlling erosion. A more recent survey of the literature reveals that coverage of 30-80% is demonstrated to prevent erosion (Dale *et al*., 2018), though it seems that > 50% achieves the most reliable results (Loch, 2000, Carrol *et al*., 2000).

The rehabilitation process does not attempt to establish an instant ecosystem that represents the targeted end use (e.g., a feedbase, native forest etc; Wali *et al*., 1999; Lamb *et al*., 2015). It takes a successional approach to revegetation wherein initial rapid vegetative cover is achieved by the sowing of short-term annual species on slopes to mitigate the risk of erosion. The intention of sowing rapidly growing annuals (e.g., Jap Millet) is to both stabilise soil while allowing time for desirable perennial species to establish in support of the identified end land use.

The conventional approach for establishing vegetative cover for grazing purposes on reconstructed landforms in the Bowen Basin generally proceeds as follows:

- Once spoil heaps are reformed into final landforms, available topsoil is placed over rehabilitated areas to a depth of 10-30cm (Figure 10).
- As appropriate, spoil materials are amended with Gypsum and/or Lime to address the risk of dispersion and low pH respectively. Some mine sites may also use OM amendments.
- To facilitate water infiltration and reduce soil bulk density, rehabilitated areas are typically ripped to a depth of 50-100cm along contours to resolve compaction caused by heavy machinery during the landforming process.
- Areas are seeded and fertilised to coincide with probability of seasonal rainfall (e.g., September – December) via aerial application or a bulldozer mounted air seeder.[40]
- A successional seed mix is applied to achieve rapid ground cover by annual species while allowing for the later emergence of perennials.
- Mining companies implement various practices to reduce the window for erosion between seeding and the establishment of vegetative cover (e.g., spreading hay across slopes).
- The trajectory of development within rehabilitated areas is regularly monitored and required maintenance undertaken to ensure they are suitable for the targeted post-mining land use.
- Livestock are generally excluded from rehabilitated areas for up to 4-5 years after initial seeding to avoid damaging the fragile surface of newly rehabilitated landforms (Grigg *et al*., 2000; Project Partner Mining Companies, Pers. Comm.).

[40] Where topsoil is unavailable mining companies invest significantly in the application of fertilisers to overcome nutrient deficiencies.

Figure 10: Re-shaped spoil-dump landforms with strategic covering of topsoil materials

Though rehabilitation manuals consulted within this project set groundcover objectives, they do not prescribe landform design and grazing management practices for supporting the achievement of this objective on variously sloped landforms that are covered with a range of spoil types.

3.1.2.2.3 Strategic goals for land rehabilitated for grazing purposes

The Queensland Government stipulates four broad goals for mine rehabilitation, namely the return of mined land to a condition that is safe, stable, has no adverse offsite impacts, and sustainably supports a beneficial end use acceptable to stakeholders (EPA 2006; Butler and Anderson, 2018). But before a mining company can relinquish land held under ML it must obtain Queensland Government certification that the disturbed land has been successfully rehabilitated to meet the completion criteria for its designated PMLU.

Mining companies develop completion criteria and performance indicators for approval by the government within EA applications which are submitted concurrently with ML applications. An approved EA authorises activities that have the potential to contaminate the environment. Within the context of open cut coal mining, EA's must define PLMU targets and the completion criteria for measuring target achievement. An appreciation for the range of grazing PMLU completion criteria currently applicable within the Bowen Basin can be gained from publicly available coal mining EAs.[41] This project reviewed all EA's for granted MLs within Queensland's Bowen Basin to understand the range of outcomes one can expect will characterise land rehabilitated for grazing purposes (Appendix 8.4). The outcomes of this review are summarised in Table 5.

[41] A coal mining site often covers multiple MLs that collectively fall under a single EA.

Table 5: Summary of completion criteria approved for grazing PMLU.[42]

Metric		Target range
Land suitability classification (LCAT) for beef cattle grazing class[43]		Predominantly classes 2-4 (9 sites) Six remaining reviewed sites did not include a land suitability target.
Land capability class[44]		< IV (one site)
Land agricultural classification		Class B (one site) and Class C (one site) 26 remaining reviewed sites did not include a land condition target.
Slope gradient and length		0% to < 5% on sodic spoil coverings Up to < 25% where stable Permian materials are available. < 10 to < 50M long
Groundcover %		40 – 60% on < 5% slopes > 50% – > 80 % for slopes up to < 25% Non-vegetative ground cover (i.e., rocks) cover < 30%
Biomass (tonne DM/ha y^{-1})		> 1
Stocking rate		Determined by: a. Undisturbed analogue site[45] (e.g., 0.22 AEU/ha) or: b. Pre-emptively defined as low intensity grazing (e.g., < 0.07 AEU/ha)
Growth medium	pH	5.5 – 8.5
	ESP	< 15%
	Salinity	< 0.6 ds/M
	Amelioration	To a depth of 200mm where required for establishing vegetation
Feedbase		Self-sustaining perennial grass and legume species that support livestock production. Preference of native grasses (11 sites) > 70% of vegetative ground cover comprises palatable species Species richness and diversity similar to analogue undisturbed sites
Weeds		Free from declared weed species or their incidence is no different from that observed on analogue undisturbed sites.
Leucaena		Leucaena < 250 stems > 2M height/ha (1 per $40m^2$) mean total area (7 sites)
Trials		Undefined grazing trials to confirm similar productivity as undisturbed analogue site. Landform is stable when grazed under a range of climatic conditions. 30-year post-mining land management plan where trials cannot demonstrate resilience.
Fencing and water		Sufficient water infrastructure installed for supporting livestock production.

[42] Data was collected from a review of EA's from 29 mine sites within Bowen Basin (Appendix 8.4)

[43] Land suitability is to be certified via a credentialled person according to the guidelines set out in DSITI & DNRM (2015). One of the partnering mining companies recognises that DSITI & DNRM (2015) does not provide a rule-set for land suitability assessment for beef cattle grazing.

[44] The system comprises eight possible classifications and refers to the overall agricultural potential of the land. Classes I to IV are suitable for cultivation with increasing level of management input required, Classes V to VII are not suitable for cultivation with decreasing suitability for grazing, and Class VIII land is not suitable for grazing.

[45] Analogue or reference sites refer to land that a company uses to verify rehabilitation success (DES 2014). These areas sit outside of rehabilitation zones and are used to compare with the rehabilitation outcomes for designated post-mining land use activities. The analogue site must have similar geographical location and landform to the rehabilitated area to minimise any differences due to weather/rainfall, climate, aspect. It also needs to have similar physical factors such as slope length, gradient, soil type, and chemical, biological, ecological and erosional factors to ensure comparison is as representative as possible.

	Livestock excluded from accessing unsuitable water, contaminated land, unsuitable sloped areas
Land maintenance	No different from that required for undisturbed analogue sites
Resilience	No evidence of vegetative dieback No bare areas > $20m^2$ or bare areas > 10M long down a slope Erosion rates comparable to undisturbed analogue sites Vegetation recovers post-grazing or after fire
Trees	Low density tree planting for providing stock shelter

The range of completion criteria presented in Table 5 captures the context and some of the unique challenges for rehabilitating these reconstructed landforms to achieve a viable and productive grazing PMLU:

A. Nearly all EAs require the mining company to demonstrate that land rehabilitated for grazing has comparable productivity to that observed for analogue undisturbed sites.
B. A reliance on the Queensland Government's Land Suitability and Assessment Tool (LCAT) for monitoring the rehabilitation trajectory of grazing PMLU land seems unsatisfactory given the tool is developed for natural undisturbed landforms.
C. The land must not have bare patches > $20m^2$ or of a length > 10 metres down a slope. This represents a significant challenge on slopes covered with sodic spoils and will require careful grazing management during dry and wet periods.
D. Rehabilitation often requires the establishment of a self-perpetuating palatable native feedbase.
E. Limitations apply to which areas are appropriate for the installation of water and fencing infrastructure (e.g. the fragile nature of the landforms may require fencing to follow ridgelines) and this could impose limitations on what grazing systems can be implemented on rehabilitated land.
F. A large area of rehabilitated land excludes the cultivation of Leucaena as a feedbase. Two of the consulted mining companies have expressed their intention to remove Leucaena from rehabilitated areas on account of its perceived weed status.

The post-mining productivity goals for rehabilitated grazing land are defined either as the equivalent of analogue unmined sites or as low intensity grazing (0.07 AEU/hectare).Oserving at their time of writing that rehabilitation of land for grazing purposes costs in the vicinity of $25,000/ha, Grigg *et al* (2000) recommended that the goal of livestock production from these areas should be to prevent degradation of this land rather than to risk rehabilitation failure through the pursuit of productivity.[46] They propose three primary objectives for establishing a feedbase on rehabilitated land:

- Achievement of a beneficial PMLU
- A sustainable and stable land surface
- Preservation of downstream water quality

The term beneficial does not necessarily mean highly productive. Discussions with mining companies and their rehabilitation manuals indicate that a beneficial outcome is

[46] A mining company partner of this project indicates that rehabilitation costs can range from $30K to $90K/ha depending on (a) the need for spoil amelioration and (b) how optimally spoil was dumped to achieve the target PMLU landform.

to achieve a geotechnically and erosionally stable landform suitable for sustainable grazing.

Recommendations for improvement

Current grazing PMLU completion criteria are largely framed by environmental concerns and were developed from observations made of ungrazed rehabilitated land (Grigg *et al*. 2001). To develop a pathway for the relinquishment of rehabilitated land for viable and productive grazing PMLU, it would seem essential to develop completion criteria that are mutually acceptable to both the mining and livestock industries. These criteria should expand beyond the present environmental considerations to include productivity and functionality indicators that scale to slope, elevation, and spoil characteristics. These scalable criteria could include:

A. Reference to an LCAT developed specifically for grazing PMLU land

It seems less than ideal to rely on Queensland Government's LCAT for assessing the condition of grazing PMLU land. For example, how is an operator to assess an area's capacity to support long-term carrying capacity for different slopes of varying spoil coverings? The rehabilitation process requires the development of an LCAT designed for assessing rehabilitated land according to slope, spoil-type, target feedbase, and age of rehabilitation. This tool would facilitate the livestock industry's evaluation of the potential for unique unnatural landforms to support viable grazing activities.

B. Productivity relative to slope and/or spoil type

Current grazing PMLU completion criteria target the production potential of land according to (a) target biomass yields (e.g. > 1 tonne/DM year^{-1}) and/or (b) achieving the carrying capacity observed for analogue grazing areas. The first criterion sets a relatively low productivity level without reference to underlying slope or growth medium characteristics. It lacks sufficient detail to the actual productive potential or how intensively the land can be grazed relative to slope or growth medium characteristics. The second criterion is more aspirational and will provide greater clarity on the viability of the land for grazing PMLU.

This report recommends that the mining industry should consider developing criteria that establishes the sustainable grazing days/100 mm rainfall/hectare year^{-1} relative to slope and spoil type. The benefits of using this approach include:

a. Provides clarity for what level of productivity a prospective end-user can expect from different areas of the rehabilitated landform.
b. Guides the end-user on the maximum number of days livestock can remain within specific areas relative to rainfall to avoid reducing groundcover.

C. Hydrological performance

The criteria would include hydrological functioning attributes relative to slope and spoil type that enhance rain-readiness of pasture. For example, the criteria could establish rainfall use efficiency (RUE) benchmarks for different slopes and spoil types that can predict pasture DM production.

D. Canopy cover

The completion criteria for grazing PMLU may need to define the appropriate canopy cover and layout relative to slope and elevation to provide shelter and optimise the microclimate for pasture growth on elevated landforms. Though some rehabilitation manuals recommend the planting of trees and/or tree belts along contoured benches, the mining industry should collaborate with the livestock industry in formally agreeing to standards required for viable and productive grazing PMLU.

E. Water and fencing infrastructure

The criteria need to account for the installation of water and fencing infrastructure that facilitate the appropriate grazing management of rehabilitated landforms. For example, they may need to define maximum paddock sizes and relative position of water points for land relative to slope and spoil type to allow for the management of livestock to reduce time spent on steeper slopes or their movement off higher risk areas during adverse weather events.

F. Adjacent undisturbed grazing area integration

The viability of grazing PMLU is likely to rely on the potential for removing livestock from rehabilitated slopes during adverse weather events or after the upper limit of grazing days/100mm rainfall/hectare year^{-1} have been utilised. It would seem appropriate for completion criteria to define the additional undisturbed grazing areas required to support the sustainable and productive use of rehabilitated landforms.

3.1.2.2.4 Current management practices for rehabilitated landforms

The mining companies consulted within this project seek to introduce grazing on rehabilitate areas as early as possible to demonstrate achievement of grazing PMLU completion criteria. This evidence is critical for obtaining certification of an area’s suitability for relinquishment. In managing these areas, the mining companies undertake to maintain a rehabilitation trajectory for achieving grazing PMLU completion criteria. A maintenance plan requires regular monitoring, preventative groundworks (e.g., water diversions), rectification works (e.g., in-filling of ground fissures), and the gradual introduction of agreed post-mining land uses.

A questionnaire used to survey the partnering mining companies on their livestock management practices for rehabilitated land revealed that this was an under-developed element of the mine closure process (Appendix 8.5). Their responses are summarised in Table 6.

Table 6: Summary of survey conducted to understand how project mining company partners manage livestock on rehabilitated landforms.

Question or topic	Mining company partner		
	Company A	Company B	Company C
Are rehabilitated areas grazed?	Yes	Yes	Yes
What is the main challenge for grazing rehabilitated land?	Gaining access on account of site safety and management system; lack of fencing and water infrastructure	Maintaining landform stability and a lack of preferential water pathways within grazing areas.	Damaging fragile land following rain events and loss of ground cover.
Grazing management system?	Continuous grazing while sufficient biomass because of a lack of fencing and water infrastructure	Livestock are introduced to rehabilitated areas for short periods. No continuous grazing.	Not specified
What management constraints are applied to the grazing of rehabilitated land?	Maximise ground cover; maintain > 1500kg DM/ha	Livestock remain in rehabilitated areas until they have removed 20% of biomass.	Utilise < 35% biomass and maintain > 1500kg DM/ha; use mature breeders that are easier to manage
Soil carbon measurements?	No	No	No
Carbon sequestration objectives?	No	No	No
Biodiversity measurements?	No	No	No
Biodiversity targets?	No	No	No

The companies interviewed held the consistent view that demonstrating that livestock could sustainably graze rehabilitated areas was critical for gaining certification that the land was suitable for relinquishment. The clearest guidelines for managing livestock on rehabilitated land were provided by Mining Partner C. Apart from setting expectations for how much biomass remained in paddocks, these guidelines instructed operators to:

- Influence the mine planning process to deliver final landforms appropriate for sustainable grazing practices (i.e., slopes < 15%; rationalising ridge locations for fencing and vehicle access infrastructure).
- Allow ridgelines to define paddocks.
- Fence cattle off from dams and watercourses

- Create "water-circles" that limit walking distance to water to < 1500M.
- Practice feed-budgeting to maintain > 1500kg DM/hectare.
- Select a beef production model that aligns with land suitability class assessment.

Of significance for this report's consideration for what opportunity the mine closure process affords the livestock industry is that the mining partners did not have established production, carbon sequestration and/or biodiversity targets for grazing PMLU land.[47] The development of a silvopastoral model considered latter in this report provides an opportunity for the livestock industry to deliver these outcomes on top of the primary maintenance and rehabilitation trajectory targets for this land.

> The mining industry does not have a scientifically validated approach to grazing management of rehabilitated landforms. The livestock industry may benefit from developing best-practice guidelines for maintaining landform stability on a range of slopes and spoil types.

3.1.2.2.5 Production potential of land rehabilitated for grazing purposes in the Bowen Basin

Possibly because the primary goal for rehabilitation relates to the achievement of stability and sustainability of a landform for grazing purposes, few peer-reviewed studies attend to the production outcomes of rehabilitated land in the Bowen Basin. The available studies report that best-practice land-forming, spoil amendment, and vegetation establishment can achieve as good, if not better outcomes for livestock production than undisturbed areas.

In the Hunter Valley, NSW, Griffiths and Rose (2017) reported that livestock production was as high or higher on rehabilitated land than on adjacent undisturbed land. Grigg *et al* (2001) observed the same outcome for rehabilitated land in a review of grazing trials conducted within this region in the 1980s. These studies, however, related to rehabilitated land in a temperate region that has relatively uniform rainfall pattern, permitting the establishment and maintenance of highly productive and digestible temperate pasture species (e.g., *Lolium perenne*). Furthermore, the rehabilitated land was covered with adequate topsoil (i.e., 10cm deep) and received repeated fertiliser applications (Grigg *et al*., 2001). Thus, the rehabilitation outcomes of grazing PMLU in the Hunter Valley are not immediately transferable to the semi-arid subtropical region of the Bowen Basin where most rain falls during the summer months, topsoil is limiting, and low carrying capacities make annual applications of fertiliser cost prohibitive.

In the Darling Downs, Queensland, Bisrat *et al* (2021) compared the biomass yield and liveweight gain/hectare on rehabilitated land with undisturbed, albeit historically degraded cropping land. They found that the rehabilitated areas supported the same or higher productivity than the undisturbed land. Two key differences between this study and the context for rehabilitation within the Bowen Basin seem noteworthy. First, topsoil was available for spreading to a depth of 30cm on rehabilitated land within the

[47] Since mining companies are required by law to rehabilitate disturbed areas, it seems unlikely that they can register carbon projects for accessing Australian Carbon Credit Units (ACCU) on this land. Unfortunately, the Australian Government's Clean Energy Regulator were unable to confirm if this is the case. Even without accruing ACCUs on rehabilitated land, improved soil water retention provides motivation for engaging in activities that sequester carbon.

Darling Downs study and this is not always possible for rehabilitation in the Bowen Basin. Second, the evaporation to precipitation ratio is about 2.5 in the Darling Downs compared to 3.9 in the Bowen Basin. This observation suggests that there is significantly less soil moisture for establishing new vegetation in the Bowen Basin, a problem exacerbated by a reliance on overburden materials inherently low in OM and, consequently water holding capacity.

In the Bowen Basin, Grigg *et al* (2000) identify the lower RUE of rehabilitated landscapes as posing the primary challenge for producing pasture and adequate carrying capacity. RUE is be expected to be lower on these landscapes because of the greater water run off caused by unnaturally high slope gradients of reconstructed landforms; lower hydraulic conductivity of suboptimal spoil materials (i.e., sodic, and dispersive); lower water holding capacity of these spoil materials; and lower relative humidity due to higher wind velocities experienced on the elevated and denuded landforms. The pasture yields resulting from the lower RUE for rehabilitated landforms leads them to suggest that relatively low carrying capacities may need to be accepted for some rehabilitated areas (*c.* 0.16 AEU/ha). Since these areas represent a relatively small proportion of larger undisturbed grazing areas, they recommend that the latter be used as a base for offering light grazing of the former in such a way that preserves ground cover and land stability, rather than a means for increasing productivity.

Nevertheless, Bisrat *et al* (2004) has demonstrated the potential of some rehabilitated grazing land in the Bowen Basin to achieve similar production levels to undisturbed grazing land within this region. Using ungrazed mown plots at three mine sites, they observed that pasture production and RUE at two of these sites (Blackwater, Norwich Park) were comparable and at a third site (Goonyella) considerably lower than unmined land. Though this study underlines the potential for some rehabilitated grazing land to support livestock production, its use of ungrazed mown plots does not account for the impact grazing rehabilitated slopes may have on pasture yield and RUE. Their study reported that RUE is negatively correlated with factors that reduce water infiltration, especially increasing slope and decreasing groundcover. Further work is required to understand appropriate grazing management of slopes to maintain sufficient groundcover for supporting an adequate RUE.

It seems noteworthy that the present project has not identified peer-reviewed grazing studies for grazing PMLU in the Bowen Basin. Moreover, mown plot studies conducted on ungrazed rehabilitated land anticipate grazing activities will be limited to the use of cattle. This project recommends that future research consider the benefits of integration of smaller ruminants within a system aimed at achieving completion criteria for viable and productive grazing PMLU.

Observation: The conventional approach to rehabilitating grazing PMLU land understandably focuses on the achievement of landform stability and sustainability. Though some studies have demonstrated the potential for this land to achieve comparable production to undisturbed grazing land, further research is required to:

- *Determine appropriate grazing practices relative to slope for maintaining sufficient RUE on sloped land to support viable livestock production.*
- *Evaluate the use of small ruminants to manage groundcover and thereby RUE on sloped landforms.*
- *Identify alternative commercial opportunities for increasing the economic activity from grazing PMLU land (e.g. commercially relevant tree belts).*

3.1.2.2.6 Opportunities for the livestock industry

At a higher level, the opportunity land rehabilitated for grazing purposes affords the livestock industry can be considered within the context of the Queensland's Government's requirement that this land is (a) safe to humans and wildlife; (b) non-polluting; (c) stable, and (d) able to sustain an agreed post-mining land use While mining operations are heavily invested in ensuring outcomes (a) and (b), the livestock industry may partner with mines in the achievement of (c) and (d). On the one hand, mining companies seek to introduce livestock to rehabilitated landforms to demonstrate that they can sustain this activity as a PMLU. On the other hand, mining companies must ensure that the introduction of livestock supports the achievement of rehabilitated targets rather than destabilise the fragile new landforms.

The mine closure process, however, presents more specific needs for which the livestock industry may offer solutions, such as:

- Livestock industry support for scientifically verified completion criteria for viable and productive grazing PMLU
- Grazing management practices for maintaining groundcover, plant diversity, and productivity on sloped landforms
- Sustainable management of grazing PMLU slopes during adverse weather events
- Resolution of bare patches on sodic and dispersive spoil coverings
- Carbon sequestration for improving soil water holding capacity of spoil covered slopes
- The establishment of alternative revenue streams from land that may have a qualified carrying capacity
- Ongoing monitoring and assessment of rehabilitated landforms beyond mine closure
- Training of graziers with skills to manage rehabilitated mining land.

A higher-level opportunity that the rehabilitation of open cut coal mines presents for the livestock industry is the development of a grazing management model that facilitates the rehabilitation of as much land for grazing PMLU as possible. This model needs to focus on the achievement of completion criteria for viable and productive grazing PLMU on sloped landforms.

3.1.3 Summary of opportunities the mine closure process affords the livestock industry

The foregoing consideration of opportunities and challenges the process of mine closure affords the livestock industry may be summarised as follows:

3.1.3.1 Undisturbed grazing land

A considerable proportion of mining owned or managed land will remain undisturbed following mine closure. Of the 760,627 hectares of this land in the Bowen Basin, 202,931 hectares sit adjacent to ML areas. The majority of the remaining 557,696 hectares of ML land will also remain undisturbed by mining activities at mine closure. Therefore, the mine closure process may relinquish significantly more than 500,000 hectares of undisturbed land from its presently owned or leased land assets, up to 90% of which will have relevance or livestock production.[48]

Interviews with this project's mining company partners revealed that the undisturbed grazing land they own is typically degraded by historically suboptimal grazing practices. Except for setting maximum tolerances for ground cover and weed prevalence, the companies do not currently have strategic objectives for the productivity, carbon sequestration, or biodiversity values of their undisturbed land. There is an opportunity for the livestock industry to partner with the mining industry in developing and achieving these objectives.

All three partnering mining companies share a common commitment to exploring opportunities for achieving net zero operational greenhouse gas emissions by or before 2050, though it seems likely that this commitment is shared by all mining companies operating within Queensland's Bowen Basin.[49] Moreover, two of the three partnering companies are committed to delivering no net loss or a net positive impact on biodiversity.[50]

The more than 500,000 hectares of predominantly grazing land currently owned or managed by these companies that is likely to remain undisturbed beyond mine closure represents a significantly opportunity for the livestock industry to service the delivery of carbon offsets through appropriate management of grazing and tree establishment. In this regard, the project anticipates an opportunity for the livestock industry to develop a silvopastoral approach for sequestering above and below ground carbon, building biodiversity, and restoring other environmental services on mining owned and managed land.

Though the grazing land adjacent to ML areas is already available for commercial livestock production, ongoing mining operations mean that reliable access to undisturbed ML land may not occur until mine closure.

[48] As already acknowledged, it is not possible to determine how much ML land will be disturbed before title relinquishment. The figure of 500,000 hectares mentioned here includes the 202,931 hectares of adjacent non-ML land plus an assumption that more than 50% of ML will remain undisturbed. The latter percentage may eventuate to be significantly higher.

[49] BHP: Pathways to Net Zero (P2NZ); Glencore, *Pathway to Net Zero* (Climate Report, 2020); Anglo American, Climate Change Report 2021.

[50] BHP and Anglo American employ a mitigation hierarchy (i.e. avoid, minimise, rehabilitate, compensatory actions for any residual impacts) to achieve a minimum of net zero biodiversity loss across their respective operations. See BHP, ESG Roundtable (September 2021); Anglo American, Our Sustainability Plan (2021).

3.1.3.2 Rehabilitated grazing land

This report has acknowledged a distinction between the land disturbed by underground longwall and open cut methods respectively. The project assumes that the former type of disturbance is primarily limited to subsidence and that this has a relatively minor impact on extensive grazing as a PMLU. Therefore, this report assumes that the opportunities this type of disturbed land has for livestock production are like those for undisturbed historically degraded grazing land. The exception may be the design and development of a silvopasture that takes advantage of hydrological changes caused by trough and peak subsidence.

The opportunities afforded to the livestock industry by land rehabilitated following open cut coal mining can be summarised as follows:

A. Collaboration on the development of completion criteria for grazing PMLU

A consideration of current coal mining EAs revealed that the mining industry is yet to develop scientifically informed and livestock industry supported completion criteria for viable and productive grazing PMLU. The livestock industry may benefit from proactively engaging with the coal mining sector to assist in the development of criteria that provides graziers with the confidence to acquire relinquished mining land for productive and profitable livestock production. The development of these completion criteria should be accompanied by the creation of an LCAT tool for assessing the rehabilitation trajectory of grazing PMLU landforms.

B. Scalable topsoil production on spoil covered landforms

There is an opportunity for the livestock industry to develop and implement production practices that increase soil OM to support livestock production as a resilient PMLU by improved soil water holding capacity. This report considers how the use of grazing practices that stimulate root growth and maintain adequate tree cover support the building of topsoil on rehabilitated landforms by:

a. Reducing the loss of topsoil materials via wind and water erosion
b. Providing a passive source of soil carbon via litter drop from the strategic use of leguminous trees
c. The use of municipal liquid biowaste in the establishment of tree-lined contours

C. Prevention of erosion

Erosion represents one of the primary risks for the achievement of grazing PMLU completion criteria. There are opportunities for the livestock industry to develop and implement grazing management practices and silvopasture designs that maintain adequate groundcover and tree shelter belts for minimising erosion by increasing water filtration and reducing wind speeds.

D. Adaptive management practices for responding to weather events

The project has revealed that mining company partners identify the presence of livestock as posing a risk for the stability of rehabilitated landforms during and after adverse weather events. The sometimes sodic and dispersive nature of covering materials makes it preferable to remove livestock from slopes when these become wet. The development of adaptive grazing management practices that can overcome these risks would benefit the maintenance of rehabilitation trajectories.

E. Building and maintaining a biodiverse feedbase

The majority of EA's reviewed for the Bowen Basin stipulate that native species should predominate on grazing PMLU land. This project entertains the possibility that appropriate grazing management practices may favour the establishment and maintenance of desirable native grasses. There are also opportunities for developing native grass seed licks for renovating or enhancing native seed banks via the deposition of livestock manure.

F. Diversifying revenue streams to enhance PLMU productivity

The Queensland Government requires that a safe, stable rehabilitated landform sustainably supports a beneficial end use acceptable to stakeholders (EPA 2006; Butler and Anderson, 2018). Where a rehabilitated area's capacity to support profitable livestock production is heavily qualified by biophysical limitations, it may be possible for graziers to introduce complementary land management practices that create additional revenue streams.

G. Operating landforms as managed ecosystems

Mining companies are obliged to monitor and assess rehabilitated land to demonstrate the achievement of completion criteria. There seems scope for the livestock industry to develop management systems that fulfil these monitoring and assessment requirements. To anticipate, graziers may be able to operate rehabilitated landforms as digitally managed ecosystems that provide a passive source of monitoring and assessment data.

H. Accelerating certification of land as rehabilitated for grazing purposes

The certification of land as rehabilitated is required before it can be relinquished for offtake by another landowner. The project has identified that there may be opportunities for the livestock industry to facilitate the acceleration of this process by using alternative grazing strategies that may include the use of small ruminants (e.g. goats).

3.1.4 Anticipating a potential business model

The project has undertaken to develop a business model for the livestock industry's integrated delivery of environmental optimised production services on (a) undisturbed and (b) rehabilitated landforms on mining land. Except for one mining company that owns its own pastoral company, the companies often lease their undisturbed land to the previous landholders or to peripheral landholders. The extent of management conditions imposed upon the lessee is typically limited to the maintenance of adequate groundcover and weed control. The mining company may also provide access for the lessee to graze livestock on rehabilitated landforms for the purpose of demonstrating the achievement of completion criteria with more stringent guidelines and oversight (i.e. the "active management and monitoring phase"; Rolfe *et al*., 2018).

This project emerged from several mining companies indicating that they would consider prioritising agistment arrangements with livestock producers who can achieve strategic objectives for undisturbed and rehabilitated mining land:

A. Strategic objectives for undisturbed land

The objectives include maintaining adequate groundcover, improving land class, increasing biodiversity, and generating carbon offsets for operational emissions.

B. Strategic objectives for rehabilitated landforms

The mining companies seek the development of management practices that enable the rehabilitation of as much land for grazing PMLU as possible. The focus of these practices should be to achieve completion criteria for viable and productive grazing PMLU by building soil carbon and biodiversity, maintaining adequate biodiverse and palatable groundcover on a range of slopes, preventing erosion, and delivering resilient livestock production from sloped rehabilitated land. By integrating management practices for achieving these outcomes within a scalable model, the livestock industry may offer a service for facilitating the achievement of land relinquishment.

The business model proposed within this report seeks to deliver services and benefits for both mining companies and livestock producers:

A. Mining Companies

In addition to providing a framework for keeping lessees accountable in the delivery of the required environmental services, the business model seeks to deliver the following benefits for mining companies:

a. Biodiverse carbon offsets

The model provides for the delivery of biodiversity and carbon offsets via the assisted natural regeneration of native tree belts on undisturbed mining land. The use of virtual fencing technology will enable the grazing of this land while permitting the regeneration of naturally occurring vegetation along pre-defined belts. The alignment of grazing activities to prioritise the emergence of desired native grasses shall also increase biodiversity on these areas.

The model proposes that carbon sequestered in addition to what is required for offsetting livestock operation emissions accrues to the mining company.

b. Confidence to target grazing as a beneficial PMLU for a larger proportion of rehabilitated land

The proposed model needs to provide an empirically based method for achieving completion criteria for as much grazing PMLU as possible. The focus of the model is to achieve this outcome for sloped landforms.

c. Maintenance of a rehabilitation trajectory that supports resilient livestock production from rehabilitated landforms

The use of emerging digital technologies within the model provides mining companies with an opportunity to outsource a pre-defined management model for rehabilitated landforms that delivers (i) maintenance of required groundcover, (ii) protection of fragile land from adverse weather events, (iii) and resilient livestock production from land rehabilitate for grazing purposes.

d. Accelerated relinquishment of rehabilitated land

By partnering with the livestock industry in developing a model that manages rehabilitated landforms for productive, profitable, and sustainable beef production, mining companies seem better placed for relinquishing this land for its PMLU.

B. Livestock Producers

The proposed business model will benefit livestock producers who are prepared to implement practices that support the achievement of pre-defined environmental and production objectives. These benefits include:

a. Access to undisturbed and rehabilitated mining land

The mining companies have indicated that affordable lease conditions are typically offered to previous or peripheral landholders. The business model proposed here may increase competition for these leases if their management leads to additional financial benefits.

b. Infrastructure

Graziers surveyed within this project argued that the delivery of the kind of environmental services required by the mining companies (e.g. biodiversity and carbon offsets; maintenance of groundcover etc) requires the installation of significant fencing and water infrastructure. Given that they access this land as leasehold, they indicated that it would be essential for the mining company to provide the infrastructure required to support the required management practices.

c. Carbon neutral certification

The surveyed graziers recognised that the mining companies desire to engage their services to build biodiversity and carbon offsets. A potential incentive for their achievement of these offsets could be a mechanism that allows producers to offset their own carbon emissions generated from their operations on this land. This report recommends that carbon sequestered via the proposed silvopastoral approach only accrues to the mining company after the initial offset of grazing operations. This approach would provide an opportunity for the grazier to benefit from the carbon neutral certification of livestock produced from mining land.

d. Diversification of revenue streams

The proposed model anticipates the generation of alternative revenue streams from some rehabilitated landforms. For example, it considers the establishment of trees that support wattle seed and honey production post-mine closure. The rehabilitation process already necessitates the mining industry's investment in planting trees on reconstructed landforms. Potential end-users could benefit from consulting with mining companies in determining what tree species should be planted.

e. Consultation on post-mining land use development

By servicing mining owned or managed land, livestock producers gain an opportunity to contribute to its design and development for grazing PMLU.

f. **Confidence to acquire land containing rehabilitated landforms**

Graziers who gain experience managing rehabilitated landforms contained within larger properties undisturbed by mining would seem more equipped and likely to acquire these properties.

The following section attempts to assemble an inventory of practices landholders presently use to remediate degraded land in the Bowen Basin. The objective is to identify what practices may be incorporated within a scalable model for servicing mining owned and managed land within this region.

3.2 Inventory of practices used for remediating degraded land types in the Bowen Basin

This project has undertaken to identify and verify silvopastoral practices that some graziers have implemented to achieve the successful remediation of degraded land. In doing so it has assembled an inventory of these practices from information and data gathered via online surveys, emails and phone interviews, and field visits (Appendix 8.2). Though the initial online survey was distributed to > 70 graziers, at least 12 of the 14 respondents identified that they actively engage with Resource Consultancy Services (RCS). This led to a uniformity in the underlying principles that governed the practices implemented by these practitioners.

Thirteen of the fourteen online survey respondents estimated that the implementation of practices aimed at remediating degraded land had improved their land class by at least one unit.[51] Phone interviews were conducted with all but three of the survey respondents. These interviews uniformly revealed that they had adopted or developed remediation practices in response to deteriorating land condition. Only five respondents reported that they undertook a cost-benefit analysis for investing in the additional time and infrastructure required for practice implementation. In this regard, they calculated that the return on investment (ROI) on the installation of an extensive drinking water system required for their grazing method by estimating the greater access this would give cattle to underutilised pasture. The ROI was estimated to cover this cost even before other practice co-benefits were considered (e.g. increased pasture productivity, biodiversity, carbon sequestration).[52] The respondents who did not undertake a cost-benefit analysis said they invested in the new practice implementation because (a) the logical argument for why these practices should work made sense, (b) they had witnessed the positive outcomes of these practices on other properties, and (c) they felt it was the ethical thing to do (e.g. managed regrowth of trees).

To evaluate the benefits respondents attributed to the documented remedial practices, the project interviewed four respondents at further length and visited three of their properties to gather additional historical data. These respondents were chosen because of the length of

[51] The fourteenth respondent indicated that the practices had maintained a Land Class B.

[52] For example, Property D (Gogango) calculated a 100% ROI/year on their water infrastructure on account of the impractical distances between water and the extent of available feed. In fact, they paid this infrastructure off over two years because they initially lacked the confidence to buy the requisite number cattle to utilise extra feed. Property C (Baralaba) estimated that increased pasture utilisation would yield a 40% ROI on the fencing and water infrastructure costs associated with their practices.

time they had implemented practices (> 8 years) and their possession of relevant historical data. The data categories these four graziers provided as evidence for the successfulness of these practices included:

- Improvements in Agricultural Land Class condition.
- Improvements made in stocking days per hectare/100mm of rainfall (SDH/100mm)
- Improvements in ground cover relative to conventionally managed neighbouring properties.
- Soil nutrient analysis
- Reductions in surface water turbidity
- Images for comparing historical improvement or present status against adjacent conventionally managed land

Biocondition assessments were obtained for Property A (Rolleston) and Property D (Gogango).[53] A Biocondition score provides "a measure of how well a terrestrial ecosystem is functioning for biodiversity" (Eyre *et al*., 2015) and indicates the extent to which functional attributes of a site correspond to those of a reference site approximating pre-European ecosystem conditions. Since there are no published Biocondition surveys for conventionally managed properties in the Bowen Basin, a review was conducted of publicly available Biocondition assessments of grazing land reported within Environmental Impact Statements (EIS) for this region (Table 7).

Table 7. Biocondition scores for Property A (Rolleston) and Property D (Gogango) compared with scores published in EIS for grazing land at Baralabah, Middlemount, and Moranbah

Location	Average Biocondition score (/100)	Range (/100)	Reference
Property A (Rolleston)	45	16 – 56	QTFN*
Property D (Gogango)	47	15 – 82.5	QTFN*
Baralabah North Project	52	37 – 74	Baralaba North 2014
Middlemount South Mine	58	43 – 72	Middlemount South 2010
Caval Ridge Mine (Moranbah)	51	32 – 60	Caval Ridge Mine 2021

*The QTFN publication details are withheld to protect the privacy of property owners.

Though the data presented in Table 7 cannot be used to make statistical comparisons, they caution the view that the livestock practices implemented at Property A (Rolleston) and Property D (Gogango) achieve relatively superior biodiversity at a landscape scale.[54] The dominance of Buffel Grass as an "invasive exotic species", a lack of woody debris and litter due to grazing activities, and a lack of "large trees" were the primary assessable attributes that reduced scores by about 35 units on all properties and sites listed in Table 7.[55]

[53] The Biocondition assessments were undertaken by the Queensland Trust for Nature.
[54] This statement should be qualified by the following acknowledgements: (a) it assumes that the properties assessed in public EIS were conventionally managed and (b) each property in Table 7 is assessed against a different referent ecosystem which weakens the comparison. The purpose of Table 7 is to illustrate that the Biocondition scores obtained from the Rolleston and Gogango properties do not encourage the view that these operations are achieving superior biodiversity outcomes compared.
[55] "Large trees" are defined as "the number of living trees per hectare with a diameter at breast height (DBH) greater than the DBH threshold provided in the benchmark document" for this relevant referent ecosystem. Eyre *et al* (2015).

The data obtained from the four exemplary properties to determine that they had improved their land and productivity are presented in Table 8.

Table 8. Metrics used to verify effectiveness of a holistic approach to land remediation by exemplary graziers in the Bowen Basin

Metric	Property			
	A (Rolleston)	**C (Baralaba)**	**G (Baralaba)**	**Gogango**
Years of implementation	25	8	23	20
Improvement in land class	C → A	B-D → A	B-C → A	C → B
LSU/ha/100 mm rainfall	12 → 29.1	22 → 36	13.2 → 26	19 → 38[56]
Liveweight production kg/ha	-	40 → 60	-	-
Visual improvement[57]	Y	NA	NA	Y

Property C (Baralaba) provided 21 years of grazing chart data that illustrates an increasing trend for Livestock Units/hectare/100mm rainfall over that period (Figure 11).[58]

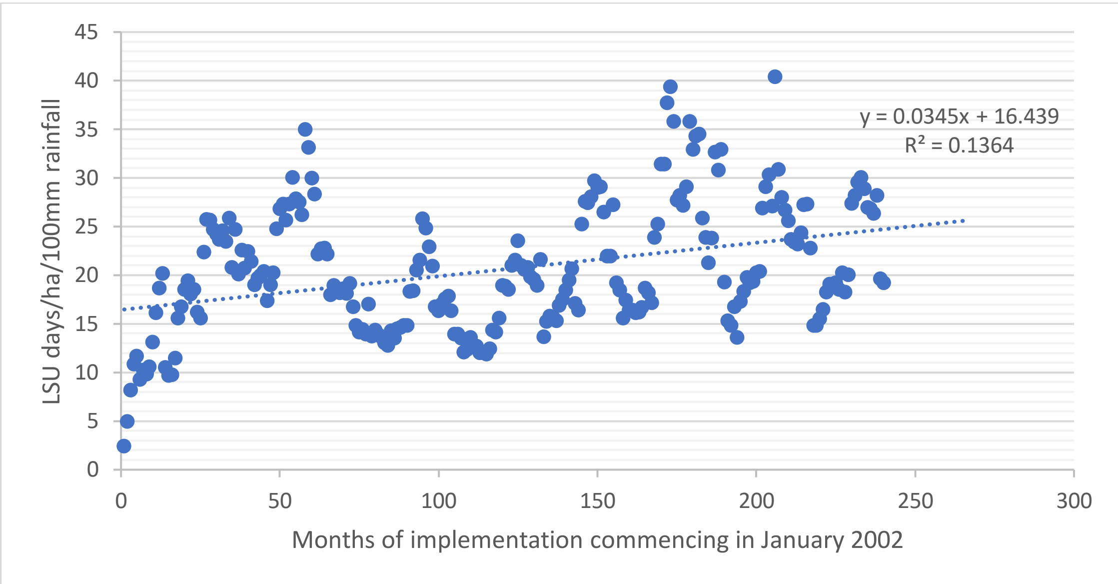


Figure 11: Rolling 12-month Livestock Unit (LSU) days/ha/100mm rainfall for Property D

Comparison data for metrics that relate to environmental services and the prevalence of palatable pasture species (3P) were obtained for properties C (Baralaba) and D (Gogango) from a Project Pioneer report funded by the Australian Government's *Reef Fund Trust* and the *Great Barrier Reef Foundation*. The comparative metrics relevant for this project are presented in Table 9.

[56] Though the Gogango property could demonstrate a trend for increased LSU/ha/100mm rainfall, in recent years pasture dieback has lost much of these observed gains. Though LSU/ha/100mm rainfall has risen as high as 38, the onset of pasture dieback within the Buffel Grass dominated pastures in 2016 has reduced the present level back to 20. Nevertheless, this landholder considers that this level is higher than it would have been had these practices not been implemented.
NA: Not available.
[57] Visual comparisons for Property C (Baralaba) and Property D (Gogango) are provided in Appendix 8.6.
[58] For the relationship between LSU and AE see McClennan *et al* (2020).

Table 9. Comparison of land, vegetation, and water flow metrics with neighbouring properties that implement conventional continuous grazing practices[59]

Comparison metric	Properties			
	C (Baralaba)	**Baralaba neighbour**	**D (Gogango)**	**Gogango neighbour**
Land Class	A-B	C	A-B	C-D
Groundcover %	81	27	86	23
Average 3P species cover %	40	8	47	3
Water infiltration time (min)	6	10	3	15
Surface water turbidity (NTU)	130.4	2,300	77.3	1,073

The design of this comparative study does not allow for the determination of statistically significant differences. Nevertheless, they present a consistent trend for properties implementing intentionally remedial practices to increase environmental services and the prevalence of 3P pasture species. The latter metric may suggest that though the surveyed silvopastoral practices did not seem to make significant improvements in overall Biocondition score, they were effective at providing a competitive advantage for desirable pasture species.

Collectively, the historical data obtained from project participants (Tables 8 & 9, Figure 12) encourages the view that their management practices improve land class, productivity, and various environmental services (e.g. water quality, groundcover). Since they regard the identified inventory of practices as contributing to a holistic approach for remediating their land, it is not possible to confirm the successfulness of individual practices by using whole farm productivity, groundcover, or environmental service metrics. For example, the effect of "time-controlled grazing" on SDH/100mm via improvements in pasture productivity is confounded by the installation of fencing and water infrastructure that facilitates greater utilisation of the grazing area. To overcome this limitation, the project has consulted the peer-reviewed literature to evaluate the likeliness of a practice's efficacy.

In addition to practices that improve land class and production, this project undertook to reveal practices that could increase carbon sequestration. The surveys and interviews undertaken, however, revealed that none of the respondents had reliable data for verifying if their practices sequester soil carbon. To address this lack of historical data, the project used historical improvements in land condition and ground cover (Cork *et al*., 2012) and the strategic retention/establishment of trees (Gowen and Bray, 2016) to gain confidence that practices were increasing soil carbon. Even so, this project recognises that the long-term retention of carbon sequestered in soil is heavily dependent upon interactions between soil mineral characteristics and weather (Mitchell *et al*., 2021). Therefore, though tree growth provides an accurate assessment of carbon sequestration, the project recognises more caution is required when using land condition and groundcover for estimating improvements in soil carbon sequestration (Bray *et al*., 2016). Studies have reported significant on property variation in soil carbon and a lack of difference between different management practices (Bray *et al*., 2015).

The following section outlines the assembled practice inventory in three parts, namely (a) the integration of trees to create a silvopasture, (b) the implementation of an adaptive grazing system that optimises feedbase growth and plant diversity, and (c) additional practices deployed for achieving missional environmental outcomes.

[59] Data has been obtained from the publication Project Pioneer, *Environmental Survey Report*, June 2020.

3.2.1 Integration of trees to create a silvopasture

All four graziers interviewed at greater length within this project practiced either the managed regrowth or strategic planting of trees on degraded areas. The estimated canopy cover of the three graziers interviewed on property ranged between 20-40%. This coverage far exceeds that found on conventionally managed grazing land within the Bowen Basin. The Queensland State Government passing of the *Brigalow and Other Lands Development Act* (1962) incentivised the clearing of grazing land to maintain shade-belts comprising of no more than 10% canopy. A combination of fires and an increasing tendency for landholders to leave few if any trees have reduced canopy coverage to less than 10% (Seabrook *et al*., 2006).[60] In 2006, Queensland ranked as the fifth region worldwide on highest deforestation rate and most of this related to clearing undertaken for beef production (McAlpine *et al*., 2009).

The practitioners claimed that their strategic use of trees realised the following benefits. An evaluation of each claimed benefit alongside the peer-reviewed literature is provided.

3.2.1.1 Environmental services

The practitioners manage the regrowth or establishment of 20-40% canopy cover on account of the environmental services they provide. This is uncontentious considering that it is well established that trees can increase the infiltration of rainwater (Ellis *et al*., 2006), nutrient cycling (McKeon *et al*., 2008), biodiversity (Felton *et al*., 2010; Evans *et al*., 2015), and water quality (Jose *et al*., 2019). In addition to the species richness associated with increasing biodiversity, the managed regrowth of trees is demonstrated to provide crucial habitat for threatened species and enhancing structural complexity (Evans *et al*., 2015). Property A (Rolleston) noted that the increased faunal diversity produced additional benefits for their operation such as supporting a higher prevalence of natural predators that reduced their exposure to pests (e.g. < mice plagues). Furthermore, they observed that increasing tree canopy coverage encouraged the diversity of pasture species by diversifying within paddock habitats. Several respondents mentioned that more palatable native grasses seemed to predominate adjacent to tree belts where they received significantly more shade. This effect has been verified by studies cited in Scanlan (2002).

3.2.1.2 Enhanced microclimate for optimising pasture growth

The retention of trees within paddocks is used by these practitioners to increase overall farm productivity by enhancing the microclimate to optimise pasture growth conditions. Trees, especially the strategic use of tree-belts, influence the microclimate of pasture areas through several processes (McKeon *et al*., 2008):

a. Direct interception of rainfall and solar radiation by the tree canopy
b. Changes in light quality (e.g. increased diffuse radiation)
c. Shading of adjacent zones, particularly in the morning and afternoon

[60] A negative attitude to allowing the regrowth or establishment of trees across grazing areas remains evident within banking culture. Some landholders interviewed within this project indicated that banks attribute lower values to tree-covered properties, thus making more difficult to borrow against equity.

d. Changes in wind speed with consequent changes in air temperature and potential evapo-transpiration, both within the tree strip and at distances several multiples of tree height away from the strip
e. Night-time cooling
f. Changes in relative humidity or vapour pressure deficit both under the tree canopy and across the transect as a result of shading, wind, and temperature.

Two producers cited evidence that tree canopy coverage between 20-30% had maintained or increased pasture productivity. On the one hand, the Property D (Gogango) managed the regrowth of approximately 30% canopy cover over a 20-year period while maintaining, and in some years increasing the SDH/100mm rainfall. Property C (Baralaba) pointed to the same metric, albeit collected over just a 12-month period to suggest that productivity is increased by the regrowth of 20-30% canopy comprising Brigalow and Black Wattle. From November 2020 to November 2021, two paddocks with this level of canopy cover supported an average stocking density/ha (SDH) of 36.4 (25.2ha) and 33.6 (27.9ha) respectively. Two adjacently situated tree-cleared paddocks on the same land type recorded an average SDH of 21.6 (24.5ha) and 26.1 (19.8ha) respectively. This data is not cited to prove that 20-30% canopy cover always leads to higher SDH, but that it seems worthwhile exploring the potential for managing the regrowth of canopy cover to achieve an improvement in pasture productivity.

The producers did not dispute that canopy cover can increase only so far before it causes pasture production to decline. Scanlan (2002) observes that studies variously demonstrated a linear decline, concave decline, or an initial stimulatory effect followed by a decline in pasture production relative to increasing tree canopy cover. In reviewing previous studies, he concludes that the influence of tree canopy cover on pasture production will depend on “the relative strengths of stimulatory and competitive effects of trees on grasses” (Scanlan 2002). On the one hand, trees may improve growing conditions by increasing the soil fertility, enhancing the microclimate for growing conditions, and water retention in soils (Scanlan 2002). On the other hand, Scanlan (2002) comments that trees also compete for light, nutrients, and water. When these competing and stimulatory effects are taken into consideration, it is to be expected that the influence of trees on pasture productivity will depend on such variables as annual rainfall, tree species, pasture species, pattern of tree canopy layout within paddocks (i.e. belt, random, tree lined contours etc), the physical and chemical properties of the soil, land aspect and no doubt grazing management.

Nevertheless, sufficient experimental evidence suggests that the relationship between tree canopy retention and open paddock productivity can be managed to avoid significant losses in farm productivity. For example, McKeon *et al* (2008) observed 0-5% reductions in pasture productivity for tree-belt and open paddock configurations studied in Central Queensland. They concluded that the benefits tree belt retention had on diet quality, nutrient cycling, hydrology, biodiversity could potentially offset losses in pasture productivity of up to 5-10%. Since the publication of their study, the development of the carbon market provides an additional opportunity to offset these losses.

The relatively lower rainfall for the Bowen Basin provides additional potential for the integration of canopy cover to increase or maintain pasture yield. In a review of the literature, Scanlan (2002) observed that the impact of tree canopy on pasture productivity seems to lessen with decreasing annual rainfall. Figure 12 illustrates that at annual rainfall averages for the Bowen Basin (i.e. 550-650mm), pasture production within treed paddocks as a percentage of production in cleared (i.e. "open") paddocks varied between 50 and 180%.

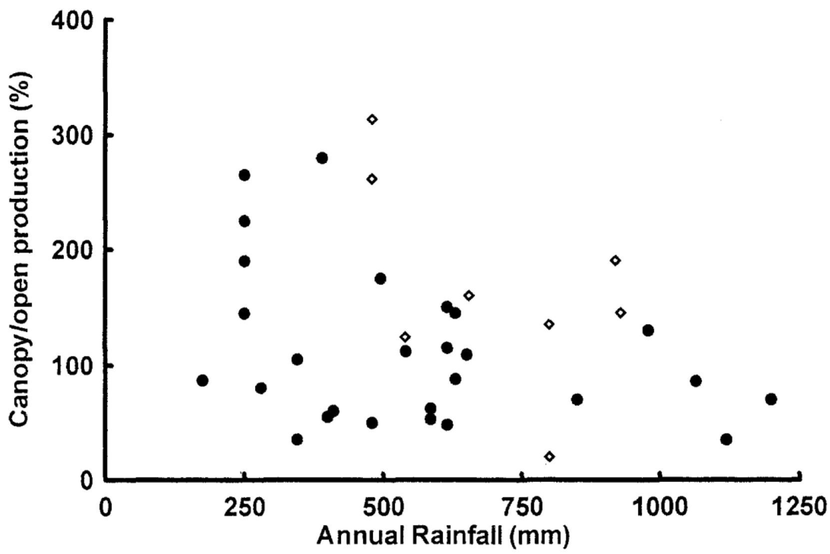


Figure 12. Relationship between above-ground pasture production (expressed as a percentage of the production open paddock areas) and annual rainfall. Source: Scanlan (2002)

Considering that many EAs for mine sites within the Bowen Basin require the establishment of trees within grazing areas, more investigation seems warranted into the most effective practice for maintaining or increasing pasture production where canopy cover is > 10%. At a microscale level, the establishment of strategically designed silvopastures on rehabilitated landforms has the potential to increase groundcover for the purpose of reducing erosion and increasing feedbase productivity. Lower relative humidity caused by elevated reconstructed landforms may challenge the establishment of a profitable feedbase on sloped rehabilitated landforms within semiarid regions. Studies conducted within semiarid environments demonstrate that well-designed silvopastures reduced direct solar radiation and windspeed by about 50% compared to open pasture control areas (Houerou, 1987; Alam *et al.*, 2018). Consequently, potential evaporation was reduced by about 70% and grasses remained greener for longer (Hourerou, 1987). Karki and Goodman (2015) reported that air temperature under a silvopasture canopy was 2.3˚C lower and soil temperature (5cm below the surface) was 2.1˚C lower than that observed for conventional open pastures.

3.2.1.3 Carbon sequestration

The practitioners regarded their management of the regrowth or establishment of trees as a means for sequestering aboveground carbon to offset their emissions as well as providing a potential source of revenue from carbon markets. Since the project was unable to obtain direct measurements for how much carbon the 20-40% canopy cover had sequestered, the Full Carbon Accounting Model (FullCAM) has been used to estimate this for respective localities of the participating graziers. FullCAM is the model used by the Australian

Government for modelling greenhouse gas emissions from the land sector. Its results are used to produce the annual totals for Australia's National Inventory Reports.

The modelling exercise determined the carbon sequestered/hectare in trees and debris over a 30-year period generated by planting "mixed environmental plantings" at a density of > 1500 stems/ha belts that covered 20% of the property. The results are presented in Table 10. The self-reported carrying capacity (AE/ha) of project participants was used to estimate the methane emissions (CO_2Eq t/ha y^{-1}) for an AE (450kg) growing at 0.4kg/day.[61] All carbon measurements are presented as carbon dioxide equivalents (CO_2equiv) tonnes/hectare.

Table 10: The capacity of trees to sequester carbon relative to produced livestock methane (450kg, 0.4kg/day liveweight gain) emissions over a 30-year period for 20% belt plantations (> 1500 stems/hectare)

Property	AEU/ha	Methane emissions (CO_2Eq t/ha y^{-1})	Carbon sequestration in trees (CO_2Eq t/ha y^{-1}) for 20% belt plantings	Methane emissions offset (%)/ha/year over 30 years
A (Rolleston)	0.22	0.37	2.0	543*
B (Banana)	0.4	0.68	2.0	296
C (Baralaba)	0.43	0.73	1.4	190
D (Gogango)	0.22	0.37	1.0	270
E (Dysart)	0.17	0.29	0.31	107
F (Middlemount)	0.26	0.44	0.3	68
G (Baralaba)	0.3	0.51	1.3	260
H (Clermont)	0.32	0.54	1.5	279
K (Moura)	0.5	0.85	2.0	236
M (Thangool)	0.23	0.39	2.0	527*

*Carbon sequestration rates for Property A (Rolleston) and L (Thangool) should be treated with caution (see below). They are not used for determining average carbon offset potential or sequestration ranges in the main text.

The relatively high and low carbon sequestration rates predicted for Rolleston/Thangool and Middlemount/Dysart respectively, derive from quite different Maximum Above Ground Biomass (M) spatial layer values used for these locations within the FullCAM model (Roxburgh *et al.*, 2019). Whereas the M value is 218.466 t DM/ha for Rolleston/Thangool, it is as low as 82.445 t DM/ha for Middlemount/Dysart. This project did not find peer-reviewed studies for tree carbon sequestration near Thangool. Using an older version of FullCAM Gowan and Bray (2016), however, reported that allowing 100% regrowth near Rolleston achieved approximately 30% of that predicted by the most recent FullCAM version used in

[61] Methane emissions were calculated using the dry matter intake equation in Rolfe (2010) and the methane emissions equation published by Charmley *et al* (2016).

this project.[62] Since it seems possible that the embedded M-values for Rolleston and Thangool within the current version may not reflect their real M potential, the values for these locations are omitted from further consideration.

Except for properties at Rolleston, Thangool, Middlemount, and Dysart, the modelled carbon offsets produced by growing trees is comparable to predictions published in the literature. Most notably, Doran-Browne *et al* (2018) estimate that at stocking rates of 6DSE/ha, 12.5% tree canopy coverage would be sufficient to offset *100% of total operational emissions*. Using a DSE to AEU of 8.4:1 (McLennan *et al*.,2020) this equates to a stocking rate of 0.71AEU/ha, higher than range of stocking rates reported within this project (0.17 – 0.43AEU/ha). As such, it seems in keeping with Doran-Browne *et al* (2018) that the average methane emission offset achieved by 20% canopy cover within the present project was 213% (Range: 68-296%).

Donaghy *et al* (2010) undertook bioeconomic modelling for the relative financial benefits of either (a) clearing 100% of Brigalow country, or (b) managing the regrowth of Brigalow or Eucalyptus tree strips 20 m wide every 60 m for 25 years, or (c) various plantation methods on a property within the Bowen Basin. They concluded that the retention of regrowth strips at carbon prices as low as $10/t CO2-e was the most financially viable model even after discounting methane emissions. When considered alongside the evidence that significant regrowth on the participating properties within the present study does not seem to reduce SDH, it seems that significant economic and environmental opportunities exist for implementing a silvopastoral model on undisturbed mining land.

3.2.1.4 Enhanced animal welfare and productivity

The project participants claimed that the integration of trees within their pastoral model improved animal welfare and thereby livestock production. Peer reviewed research that confirms a positive relationship between tree canopy cover and livestock production is surprisingly difficult to find. Jordon *et al* (2020) present a systematic review of the peer-reviewed and grey literature to assess, among other things, the impacts of temperate silvopastoral systems on sheep and cattle productivity. They observed that 58% of pasture production studies found an outright negative effect of canopy cover on livestock production or a negative correlation between livestock production and increasing canopy cover. Interestingly, however, they found that less than 20% of livestock growth studies observed canopy cover to have an outright negative effect. They interpret this observation as indicating that other factors such as improvements in animal welfare and pasture nutritive quality within silvopastoral systems have importance for livestock growth. It seems possible that potential losses in pasture productivity with increasing canopy cover may be compensated by improved environmental and nutritive conditions for livestock production.

[62] The figure taken from Gowan and Bray (2016) is for the managed regrowth of Brigalow across 100% of the area. The present project's use of belt plantings rather than the managed regrowth of trees across 100% of the area accounts for some of the significant difference. FullCAM estimated that belt plantings sequestered 1.4 times as much carbon compared to uniform plantings across 100% of paddock areas in this project.

3.2.1.5 Diversified revenue

The project's online survey invited participants to indicate if they had diversified revenue through the integration of trees within their livestock production system. Only one respondent reported that they generate income from the sale of timber. This project will explore opportunities for diversifying income through the strategic use of trees in the development of a silvopastoral model for remediating mining land.

Figure 13: Managed belts of Brigalow regrowth in a time controlled grazed Buffel Grass dominated pasture near Rolleston, Queensland

3.2.1.6 Relevance of silvopasture practices for rehabilitated mining land

The strategic integration of trees within a silvopastoral system has the potential for overcoming or minimising some of the challenges this report has identified for achieving viable and productive grazing PMLU on rehabilitated landforms:

A. Potential enhancement of groundcover and pasture production through favourable modifications of microclimate on elevated landforms
B. Disruption of slope length to reduce the erosive potential of rain events
C. A passive source of carbon through litter drop that increases inter-tree soil OM content.
D. Improved nutrient and water cycling that improves water quality leaving landforms
E. The potential for realising alternative revenue streams from commercially relevant trees for offsetting the qualified productivity of some grazing PMLU land.

3.2.2 Adaptive grazing management

Respondents to the initial online survey self-identified as implementing grazing “time-controlled” (11/14 respondents), “multi-camp” (2/14 respondents), or “rotational resting” (1/14 respondents) methods of grazing. No respondents implemented “continuous” grazing methods.[63] Since the “rotational resting” respondent had implemented this method for < 5 years and reported no improvement in land condition this property was excluded from further analysis. The two “multi-camp” graziers had increased their land condition by one unit after implementing this method for < 5 years and > 5 years respectively and were interviewed at length. In keeping with the “time-controlled” respondents, these operators attributed the improvement in land condition to greater grazing intensity and the recovery of pastures during rest period. They explained that time-management considerations led them to opt for a “multi-camp” grazing method that relies on > 7 paddocks/heard with calendar-based moves in preference to a more time-intensive “time-controlled” management approach. For example, the location of some grazing areas > 20km from the home of Property G made it impracticable to move cattle as regularly as required within the time-controlled method. This report focuses on the key practices described by the 11/14 respondents implementing time-controlled grazing. Nevertheless, the report still draws on responses and insights from the multi-camp practitioners to build the final inventory of grazing practices used to remediate degraded land types.

Even though respondents identified as implementing the categories of “time-controlled,” “multi-camp,” and “rotational resting,” the practitioners were uniformly committed to changing or adapting their practices to optimise the productivity and environmental services offered by vegetation, animals, and soil. It seems appropriate, therefore, to refer to the suite of practices identified within this project as *adaptive*. Defining it in this way allows for the inventory of practices to accommodate and adopt implementation strategies that fall outside of more carefully defined grazing systems (e.g. “time-controlled,” “multi-camp,” “continuous” etc).

3.2.2.1 Adapting grazing management to support the achievement of agronomic, soil, and plant diversity objectives

All graziers interviewed within this project undertake to adapt grazing management to achieve their agronomic, soil, and plant diversity objectives:

Agronomic and nutritional objectives:

- To increase and maintain groundcover
- To optimise pasture production and utilisation

Soil objectives:

- To increase water holding capacity by increasing soil OM content
- To minimise erosion

Plant diversity objectives:

[63] The grazing practices landholders implement do not necessarily fit neatly within the discrete system categories used within this project. A gradation in the extent to which rotational practices are implemented between rotational and continuous grazing systems (Sanderman *et al*., 2015). There may be examples of continuous grazing that overlap with, for example, “multi-camp” methods.

- To encourage biodiverse flora that provide environmental services
- To enhance and maintain the plant diversity of pasture species for de-risking dry periods or disease occurrence (e.g. “pasture dieback”)

This report’s consideration of the grazing principles and practices the interviewed landholders implemented to remediate land are detailed in what follows. Since these practices contribute to holistic management systems, it is not possible to use on-property data to verify individual practice effectiveness or their contribution to the achievement of the above specific objectives. To overcome this limitation this report considers the peer-reviewed literature to assess the likelihood that these practices contributed to the improved production and environmental services observed on these properties.

3.2.2.1.1 Grazing at the *optimal time* relative to plant and livestock requirements

All interviewed graziers managed grazing to optimise the survival and growth of desirable pasture species. This management approach is implemented using the following practices and governing agronomic principles.

A. Grazing at the optimal time relative to plant recovery from previous defoliation

The practice:

The practitioners managed grazing to optimise the regrowth potential of pasture species. Practically, they (a) delayed the grazing of a paddock until the pasture had recovered energetically from its previous grazing and (b) removed cattle from paddocks before the pasture commenced its recovery by re-growing new leaves.

The operators observed three pasture regrowth phases that have relevance for determining when a paddock is ready to graze:

Phase 1: Pasture plants are recovering after a previous grazing.
Phase 2: Plants have recovered from their previous defoliation and are once again ready for grazing.
Phase 3: The oldest leaves grown after the previous defoliation begin to senesce.

On property interviews with survey respondents revealed minor differences in how they managed the grazing of pastures with reference to these regrowth phases.

Property A (Rolleston): *Management aims to graze pasture in Phase 2. The grazing interval is often 90 days during the growing season, taking approximately 20% of available biomass/grazing. This operator is about to implement a new grazing regime, however, whereby paddocks will be grazed every 30 days during the growing season with much higher utilisation rates. The objective of this new approach will be to leave little available biomass for the dry season and sell cattle. Livestock are removed from the paddock after 1-2 days.*

Property C (Baralaba): *After allowing a 54-60-day rest at the beginning of the growing season, the observation that a paddock is “at the top of Phase 2” determines when it is grazed. Generally, the grazing interval is approximately 45 days during the growing season on this property. This operator aimed to achieve Phase 2 in paddocks with the arrival of the dry season, after which paddocks were* *grazed twice prior to the next wet season. Livestock are removed from a paddock within 2-3 days during the growing season and within 6 days during the dry season.*

Property D (Gogango): *Observes a 60-day rest of paddocks from the beginning of the growing season to allow roots to recover from the previous season and grazing during the dry season. After this, livestock are managed to graze pastures "at the top of Phase 2" every 30 days until the dry season. Once the dry season commences, paddocks are grazed twice over c. 240 days. Livestock are removed from a paddock after 2.5-3 days.*

Property K (Moura): *The practitioner achieves a 45-day grazing interval, livestock are removed within 3-5 days to avoid grazing new growth.*

The principle:

The practice of timing grazing relative to a pasture's recovery from a previous grazing is based upon the well-understood physiological response plants make to defoliation. After its defoliation, a plant draws on water-soluble sugars (WSC) stored in its roots and stubble to regrow new leaves (Fulkerson 2007). Once the first new leaf appears after defoliation, the plant begins to restore these energy reserves via photosynthesis. If defoliation occurs before it has fully restored this energy, the plant's energy status gradually declines, leading to slower regrowth and/or premature senescence.

For some pasture species, a specific leaf-stage of regrowth is used to determine if a pasture has restored its energy reserves to their pre-grazing level. For example, in temperate ryegrass pastures, plant energy reserves recover to their pre-grazing levels after they have grown three new leaves (Figure 14).

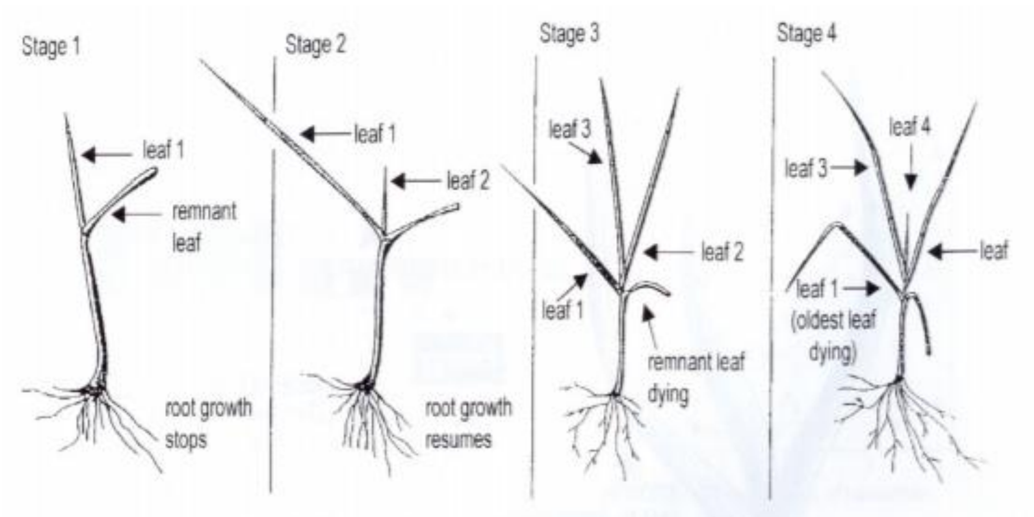


Figure 14. Stage of leaf-regrowth in Perennial Ryegrass (*Lolium Perenne*) as an indicator of readiness for grazing. After the plant's defoliation (Stage 1), the plant draws on root and stem energy reserves to regrow new leaves (Stages 2-3). After the complete replenishment of its energy reserves it is ready for a new grazing event (Fulkerson, 2007)

In keeping with the observation that plants prioritise the mobilisation of remaining energy reserves to regrow after grazing, the practitioners regard it as important to remove livestock from a paddock before livestock graze newly emerging regrowth (e.g. Stage 2, Figure 14). For example, if a defoliated plant that is desirable for livestock production begins to regrow its first new leaf after five days after grazing, cattle should be removed before this time. If they are to allowed graze this new leaf it will lead to the depletion of regrowth energy reserves, aboveground pasture biomass, root growth and plant persistence (Ordóñez *et al*., 2021).

An important co-benefit of grazing plants when they are ready to re-grow is that this both maintains and stimulates root growth. From a soil carbon perspective, the use of grazing livestock to build soil OM relies on the sequestration of carbon in root systems and their associated biota rather than on the deposition of OM in faeces. Faeces contribute relatively little OM to soils within extensive grazing operations. For example, if one animal consumes approximately 8kg DM/day of a pasture of 60% digestibility, the animal deposits 1.2 tonne DM/year of faecal OM.[64] On land that carries less than one AE/five hectares, this equates to an annual faecal OM deposition rate of no more than 0.24 tonne DM/hectare.

The primary mechanism by which grazing operations increase soil OM is through their modification of root biomass and its associated biota. For example, in a > 14-year study that compared soil organic carbon stocks underlying tropical pastures either grazed or left ungrazed, Wilson *et al* (2018) reported that plants in grazed areas allocated five times as much carbon to the expansion of root systems than what was observed in grazing-excluded areas. In keeping with this observation, the root to shoot ratio in grazed areas was 4:1 compared to about 1:1 in ungrazed areas.[65] These different outcomes can be explained in terms of the different agronomic priorities for grazed and ungrazed plants. Ungrazed pastures exhibit a sward architecture that allows plants to compete for light (e.g. larger leaves, wider plant spacing). These plants prioritise the growth of shoots over roots, and they may also initiate reproductive structures earlier than grazed plants. By contrast, grazed plants prioritise the rapid mobilisation of soil nutrients to support regrowth. Consequently, they respond to grazing by using energy reserves to grow extensive fine root systems that can access the requisite nutrients (Wilson *et al*., 2018).

This observation may encourage the use of light grazing to stimulate root development at an earlier stage of the rehabilitation process in a mining context. It may be possible to use smaller ruminants or slashing to achieve this outcome where soils are too fragile to accommodate cattle.

The overgrazing of pasture plants can have the opposite effect on root biomass by slowly decreasing root size and increasing plant mortality. Adaptively managed grazing systems attempt to graze plants when they have fully recovered from a previous

[64] A 450kg Bos Taurus steer at maintenance represents one standard AEU when calculating stocking rates. Mclean *et al* (2014).

[65] The study conducted by Wilson *et al.* (2018) occurred in subtropical Florida (USA) on sandy soils receiving 1300mm annual rainfall. The influence of grazing on soil organic carbon associated with root growth is likely to be different on finer spoil materials receiving 500-650mm of annual rainfall in Queensland's Bowen Basin.

grazing. If plants are repeatedly defoliated before new leaves generate sufficient energy reserves to regrow, the plants find it increasingly hard to recover. Their root system declines, and they will eventually die, reducing productivity and soil OM. The effect of defoliation frequency (i.e. simulation of grazing frequency) on root mass in Black Speargrass and Perennial Ryegrass is illustrated in Figures 15 and 16 respectively.

Figure 15. Effect of frequency of defoliation on the roots of Black Speargrass. The plant on the left was defoliated three times throughout its growing season. The plant on the right was defoliated every two to three weeks throughout its growing season to simulate continuous grazing (Ash *et al*., 2002)

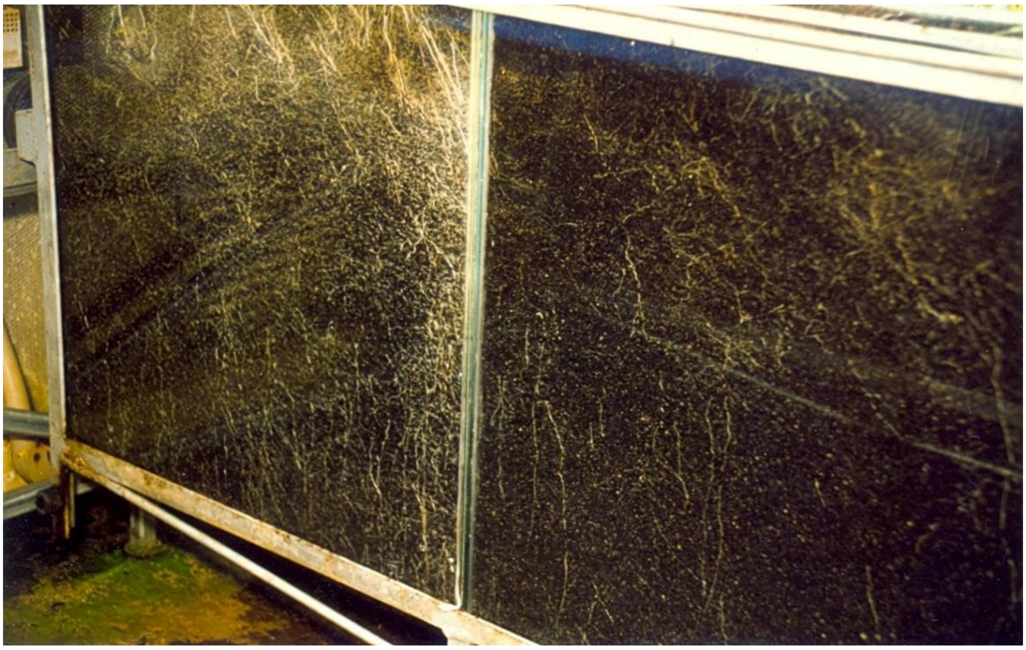


Figure 16: Effect of defoliating Perennial Ryegrass plants after they regrown 3.5 new leaves (Left) or just 1 new leaf (Right) after a previous defoliation. The plants were grown in glass soil chambers covered in foil (Donaghy 1998)

It seems noteworthy that some of the interviewed practitioners explained that the use of the "three phase" approach to determining when to graze a paddock has been developed in preference to the "leaf stage" model because of the multifloral nature of pastures used within extensive grazing operations. As has been demonstrated with C3 grass species, the recovery time of different grass species is associated with different leaf stages of regrowth. For example, the optimal leaf stage for Perennial Ryegrass (*Lolium perenne*), Pasture Brome (*Bromus valdivianus*), Cocksfoot (*Dactylis glomerata L.*), and Prairie Grass (*Bromus willdenowii* Kunth.) are 3.5, 4, 4.5, and 3-5 respectively (Ordóñez *et al*., 2021; Turner *et al*., 2006). This project has not identified any experimental evidence for a leaf-stage that indicates the optimal time for grazing pasture species used in the extensive grazing systems of Northern Australia.

Scientific evidence:

The practice of grazing pasture at a time that optimises its regrowth potential and longevity is well-established within the pasture-based dairy industry (Donaghy and Fulkerson, 1998; García-Favre *et al*., 2021; Ordóñez *et al*., 2021). Most of this work, however, was undertaken with temperate (C3) grass species. It remains unclear if the same results would apply to tropical C4 pasture species used in the extensive grazing systems of Northern Australia. There is anecdotal evidence that stoloniferous C4 grass species are less sensitive to the timing of grazing on account of the much larger energy reserves held in stolons. For example, *Pennisetum clandestinum* (Kikuyu) can withstand grazing for up to 6 days before its regrowth potential is impaired (W.K. Fulkerson, Pers. Comm).

Since the extensive grazing operations within the Bowen Basin are predominantly based on C4 exotic (Buffel Grass) and native grass species, more work is required to understand their sensitivity to the time of defoliation relative to their stage of regrowth. Though some studies report that adaptive rotational grazing strategies did not increase plant biodiversity above what was observed for continuous grazing (Holechek *et al*., 2000; Briske *et al*., 2008; Hall *et al*, 2014), other experiments have demonstrated that introducing grazing intervals (i.e. rest) can maintain or increase plant diversity (Chillo *et al*., 2015; Teague *et al*., 2015; Waters et al., 2017; McDonald et al., 2019). An understanding of when to graze plants for optimal regrowth, root development, and longevity will have importance for the encouragement and maintenance of desired native grass species on rehabilitated landforms. This information would be critical for developing grazing management practices that support mining companies to fulfil their EA requirements to establish pastures dominated by native species on land rehabilitated for grazing purposes.

> Most graziers consulted in this project moved livestock every 1-6 days. Considering that moving livestock every day is a time-consuming exercise. It seems noteworthy that this management decision is practiced without agronomic evidence that plants regrow any faster if cattle are moved as rapidly as every day. More work is required to understand how long desired pasture species can withstand repeated defoliation before it reduces their rate of regrowth.

B. Grazing at the optimal time relative to livestock nutritive requirements

The practice:

The practitioners managed grazing to optimise nutrient use efficiency from pastures. They aimed to provide livestock with access to pasture (i) when it contained its highest nutritive value for livestock and (ii) before the oldest plant leaves began to senesce. To achieve this outcome the operators aimed to graze paddocks at the "upper end" of the Phase 2 stage of regrowth immediately before plants begin to senesce in Phase 3.

> **Property C (Baralaba):** *This grazier monitors whether they are grazing pasture in Phase 2 by the appearance of livestock faeces: Phase 1: watery; Phase 2: firm; Phase 3: Woody. If watery, they need to slow down the rotation because the pasture lacks adequate fibre. If woody, they need to speed up the rotation because the pasture has lignified, senescence has commenced. Where Phase 3 paddocks require grazing, preference is given to using older cattle that have developed a palate for grazing lignified grasses.*

The principle:

In addition to maintaining a grazing interval that supports a plant's potential to regrow following defoliation, this principal assumes that a pasture's nutritive value is optimal for animal requirements at the upper end of Phase 2. Furthermore, the objective is to graze the pasture before plants begin to lignify and senesce in Phase 3. When a pasture remains ungrazed before Phase 3 its productive potential remains underutilised.

Scientific Evidence:

As for the leaf-stage of regrowth being an indicator of a plant's readiness for grazing, the relationship between stage of regrowth and the nutritive value for livestock production is well established in the pasture-based dairy industry (Fulkerson and Trevaskis, 1997). Though dependent upon the season, WSC increases from the time of defoliation until the oldest leaf begins to senesce.

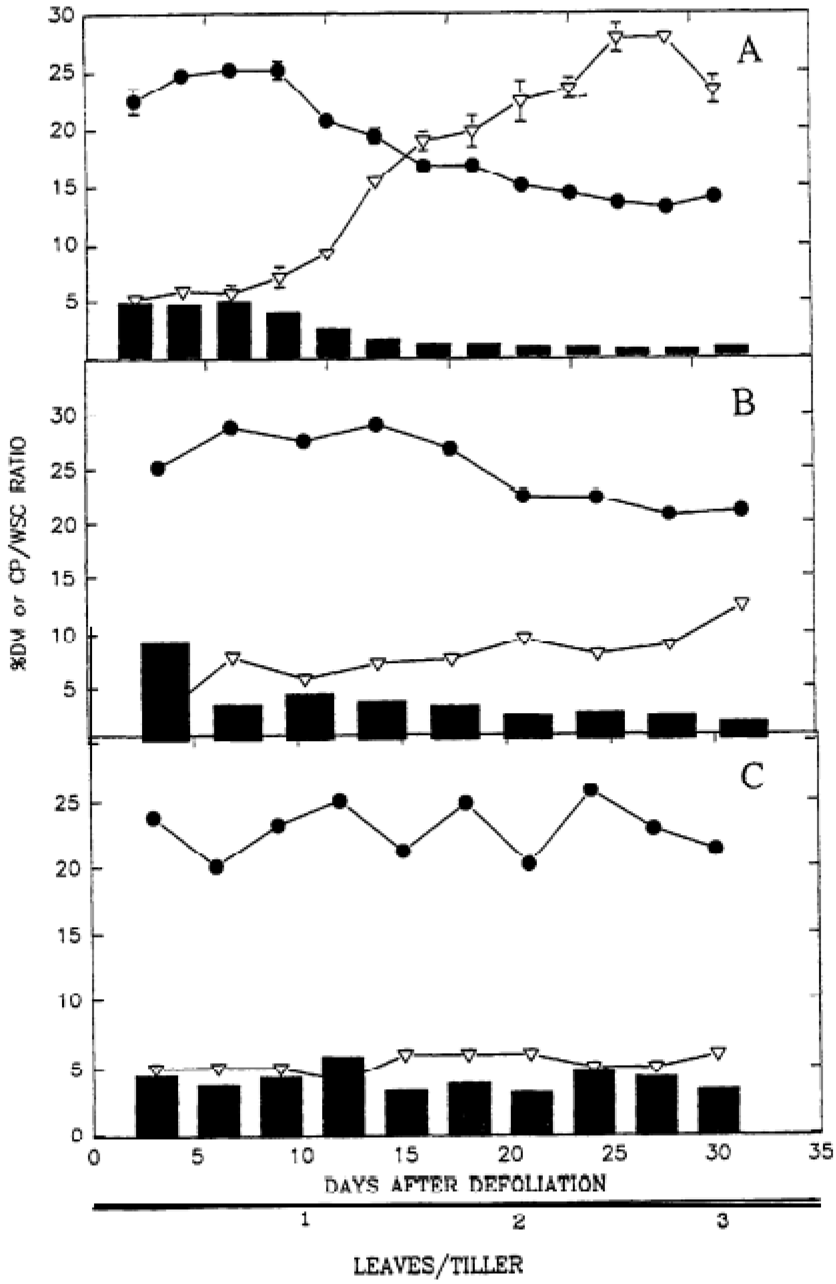


Figure 17: Percentage of crude protein (CP) (●), water soluble carbohydrate (WSC) (Δ) and the CP:WSC ration (▪) for leaf stage ("leaves/tiller") of perennial ryegrass taken at 3 hours after sunrise in July (A), September (B) and November (C). (Fulkerson and Trevaskis 1997).

A similar relationship between the stage of regrowth and nutritional quality has been demonstrated for the C4 grass species *Pennisetum clandestinum* (Kikuyu). Reeves and Fulkerson (1996) observed that the point of optimal nutritional quality for livestock occurred at the 5-leaf-stage (i.e. leaves/tiller) of regrowth.

As for previous studies on the relationship between the stage of regrowth and readiness for grazing, the work undertaken on the nutritive value of plants relative to regrowth stage is restricted to grass species used within the intensive grazing systems of the dairy industry. Though it logically follows that plant leaf material begins to senesce at some stage post-regrowth, the relative improvements realised in nutritive value remain poorly understood for the pasture grass species commonly grazed within extensive grazing systems.

Though not of immediate relevance for the rehabilitation of disturbed mining land, the project established that studies have not considered the importance of diurnal variation in plant sugars may have for increasing the productivity of rotational grazing systems within an extensive grazing context. Water soluble carbohydrates (WSC) increases during daylight hours while they are photosynthesised at a rate that exceeds their use in respiration. During the night, the WSC content declines as the plant respires in the absence of photosynthetic activity. These diurnal changes apply to both C3 (e.g. Rygrass; Fulkerson *et al.*, 1997) and C4 (e.g. Kikuyu; Reeves *et al.*, 1996) grass species. Overall, there is about a 0.5% increase in WSC/hour during daylight hours. Dairy cows consume more than 70% their daily intake within 3-4.5 hours of entering a new paddock (Trevaskis *et al.*, 2004). Fulkerson and Trevaskis (1997) estimate that a dairy cow eating 15kg DM between 3pm to 6pm would ingest 0.8kg more than if she had ingested this between 5am to 8am. In a grazing trial, Trevaskis *et al* (2004) demonstrated that the cows allocated a new paddock after 4pm produced 2.5L/cow day^{-1} more milk compared to cows provided with a new paddock at 8am.

Graziers surveyed in this project moved livestock as regularly as once/day and always first thing in the morning. Since beef cattle may similarly consume 70% of their daily intake after receiving new pasture, it seems possible that they may realise a response in liveweight gain if they prioritised moving livestock last thing in the day when pasture WSC is highest.

C. Grazing management to support environmental services

The practice: Some graziers interviewed within the project aim to graze paddocks to increase the provision of environmental services, such as soil carbon sequestration, plant diversity, and improved capture of water within soils.

Property A (Rolleston): *This practitioner manages the grazing of Buffel Grass dominant pastures to achieve a residual biomass that allows for the emergence of native grasses. Adapting the grazing pressure and interval to optimise plant recovery and growth maintains groundcover. This producer argues that the inverse occurs on conventionally managed continuous grazing operations: grazing pressure remains the same and groundcover changes*.

The practitioner prefers to have no cattle while there is no rain to maintain groundcover for capturing water when it rains (i.e. the property is "rain ready"). This practice, it was argued, to a large extent accounts for why their system responds more rapidly than conventionally managed properties after prolonged dry period.

Property C (Baralaba): *This property intentionally grazes livestock on desirable pasture species while they are seeding before moving the cattle so that they deposit seed in faeces in areas where they are attempting to establish these pasture species.*

Property D (Gogango): *A Biocondition survey conducted for this property by the Queensland Trust for Nature (QTFN) recommended that this property could increase its Biocondition score by using grazing management to increase the presence of native grasses in a Buffel Grass dominant pasture. The report recommended introducing livestock in into small paddocks for intense periods just before and during Buffel Grass seeding "to reduce its spread and promote competition with native species." This same report recommended allowing livestock to "churn the paddock, whilst supplementing native seed availability through feeding it to the cattle and directly seeding the paddock after the cattle have been removed, will likely result in increased native grass biodiversity."*[66]

Property J (Moura): *They have transformed a monoculture of Buffel Grass pasture to native grass species dominant pastures by introducing a 45 day grazing interval during the growing season that they consider favours native species.*

The Principle: The underlying principles for this practice overlap with those that govern grazing management that optimises regrowth potential and nutritive value for livestock production. Plant growth and longevity are influenced by the length of grazing interval and the severity of grazing. The practitioners attribute the comparatively superior groundcover on their properties to their practice of grazing plants when they are ready to graze. Similarly, they propose that they adapt grazing intensities and frequencies to encourage and maintain the presence of desirable native pasture species. Two of the landholders interviewed on property had data to demonstrate that their adaptive grazing management practices improved the infiltration of water into the soil and reduced the turbidity of surface water flow (Table 9). It seems arguable that an improvement in water quality was an outcome of (a) adequate groundcover and (b) the relatively short time livestock had to disturb the soil surface within paddocks.

Scientific evidence: The scientific evidence that adapting grazing management to optimise the growth and survival of desired pasture species is the same as that already discussed in relation to grazing interval and severity. The same limitation, however, applies to the use of this evidence within extensive grazing systems, namely most of the investigative work has been done with pasture species used in intensive grazing systems. Without the same basic data for the extensive grazing systems of Northern Australia, the claim that grazing management can be used to encourage the presence of native grass species in Buffel Grass dominated pastures should be treated cautiously. This project has found no peer-reviewed research to

[66] Queensland Trust for nature, [Property name withheld to protect privacy]: Protecting Threatened Species and Restoring Grazing Land (Grazing LRF; 2020).

determine the optimum grazing interval and intensity that favours native grasses, for example, over Buffel Grass.

Few studies have investigated the potential for livestock to ingest and subsequently disperse viable desirable pasture species seeds via faecal deposition (Simao Neto *et al*., 1987; Jones *et al*., 1991; Gardner *et al*., 1993; Göbulak 1998). A comprehensive Australian study (Gardner *et al*., 1993) examined the survival and subsequent germination rates of 44 tropical and subtropical legume and 28 grass species subjected to an *in vitro* rumen and acid-pepsin digestion process. They observed a positive linear correlation between seed hardness and the germination rate of seeds. Hard-seeded legumes and grasses had the highest survival rate during digestion. For example, *Leucaena leucocephala* (cv. Cunningham) retained its pre-digestion rate post-digestion and 20.8% of the hard seeded *Pennisetum clandestinum* (Kikuyu) germinated post-digestion. Interestingly, Buffel Grass (*Cenchrus ciliaris*) seed did not survive digestion. Only two native grass species were examined in the study, namely *Themeda triandra* and *Bothriochloa decipiens*. The *Themeda triandra* seed was found to have a germination rate of 0% pre-digestion so that its survival post-digestion remains unknown. And though 0% of *Bothriochloa decipiens* seed germinated after digestion, just 3% of it was viable pre-digestion. Therefore, it seems that more work is required to understand the viability of native grass seeds that undergo *in situ* digestion.

If desirable plant seeds do remain viable post-digestion, there remain opportunities to develop this practice for increasing the biodiversity of the feedbase. For example, the seed content of faeces is highest 2-3 days post-ingestion (Simao Neto et al., 1987) and highest at relatively intense grazing pressures (Jones *et al*., 1991). There is scope, therefore, to innovate strategic practices for re-seeding areas with desired plant species if it can be demonstrated that sufficient seed quantities germinate via faeces deposition (Göbulak 1998).

3.2.2.1.2 Grazing at the right intensity for managing groundcover and feedbase quality

The practice: Graziers undertake regular feed budgets that inform the stocking rates required for achieving a grazing pressure that maintains groundcover and the desired feedbase composition. The interviewed practitioners use stocking rate to apply pressure that removes 20-30% of available pasture over a 1-3-day grazing period during the growing season. A further 30% is knocked at these stoking rates and this provides greater opportunity for desirable plant species to compete with Buffel Grass dominated swards.

Property A (Rolleston): *After producing daily feed charts and budgets for more than 20 years, the practitioner intuits available feed from moving livestock daily. Sets grazing pressure to achieve 20-30% utilisation. The higher grazing pressure also assists in knocking over up to 30% of the pasture and this also allows other desirable plants species to compete with predominantly Buffel Grass (Biloela) pastures. Since their grazing method excludes livestock from each paddock for up to 350 days/year, the use of intermittent intensive grazing pressure facilitates the strategic regrowth of trees.*

> **Property C (Baralaba):** *Undertakes a feed budget for each paddock and concentrates on the presence of desirable species. The grazing pressure will be adjusted to avoid over-grazing the latter. Since the paddocks are dominated by Buffel Grass (American), the goal is to achieve a uniform heavy removal of available pasture to allow desirable species to compete. The practitioner monitors what livestock select first on entry to a paddock and what they leave upon exiting. Where selective grazing occurs, an electric tape may be used to split paddocks to enhance the uniformity of grazing by increasing grazing pressure. A feed budget at the beginning of the dry season determines carrying capacity through to the anticipated wet season. Stocking rate is adjusted to allow the removal of available pasture in two grazing episodes over the dry season.*
>
> **Property D (Gogango):** *Feed budgets are conducted 4-6 times each year.*
>
> **Note:** *Most practitioners interviewed indicated that they manage their livestock numbers to retain 30% of pasture biomass by the end of the dry season.*

A controlled uniform grazing pressure serves to maintain ground cover and the desired feedbase composition by preventing the overgrazing of patches of desired species and allowing these to compete with other less desirable species.

The principle:

This practice assumes that low stocking rates relative to pasture availability leads to selective grazing pressure of desirable plants and the avoidance of less palatable species. Consequently, the less palatable species may gradually dominate the feedbase or groundcover may reduce in areas where selective grazing pressure is applied. To prevent selective grazing pressure, the practitioners produce feed budgets that enable them to set stocking rates that prevent selective grazing, resulting in a uniform removal of biomass. Uniform intense grazing pressure and the associated “knocking down” of lignified material are viewed as encouraging and maintaining the presence of desirable palatable species within a Buffel Grass dominated pasture.

Scientific evidence:

The impact of stocking rate and grazing intensity on groundcover and feedbase composition is well understood (O’Reagain and Turner, 1992; Hawkins, 2007). On the one hand, high intensity grazing over long periods of time reduces groundcover and plant diversity (Waters *et al*. 2019). The repeated defoliation of plants increases their rate of senescence and favours the establishment of less palatable exotic plant species. On the other hand, selective grazing associated with low intensity continuous grazing may cause a decline in the prevalence of palatable grass species (Norton 1998). When livestock have room to explore the landscape, this gives rise to the severe and repeated defoliation of preferred patches, leading to the same outcome as long periods of high intensity grazing (Norton 1998).

Less agreement extends to the benefits intermittent high intensity grazing pressure punctuated by long resting intervals has for maintaining groundcover and species composition within extensive grazing operations. Whereas studies indicate that this grazing system promotes groundcover and/or plant diversity (Sanjari *et al*. 2009; Kahn *et* *al*. 2010; Teague *et al*. 2011; Teague *et al*., Sanderman *et al*., 2015, McDonald *et al*., 2019; Waters *et al*., 2009), a comparable number of studies and review articles find no difference between grazing systems when stocking rates align with pasture availability (Hall *et al*., 2014; Briske et al., 2008; Hawkins *et al*., 2017; Schatz *et al*., 2021). Norton (1998) provides a potential explanation for why differences in groundcover and plant diversity are often not observed in many comparative studies of "rotational" and "continuous" grazing systems. He attributes the lack of difference found in many studies to two observations:

A. An inability for research size paddocks to accommodate spatial variability that leads to patch overgrazing

Relatively small research paddocks do not permit the usual exploratory and patch grazing behaviour that occurs on a larger scale. Norton (1998) observes that livestock entering a new paddock generally establish an initial pattern of use and that they are attracted to areas previously grazed. This leads to intense patch grazing alongside rarely utilised areas. Teague *et al* (2008) observe that over-grazed patches generally expand and less desirable patches are avoided within continuously grazed areas. Without comparing grazing systems in larger scale paddocks, Norton (1998) contends that the main difference between the systems will not be observed.

This argument has relevance for the lack of difference between continuous and rotational grazing observed in a study conducted by Schatz *et al* (2021) which randomised three grazing treatments across 26 x 6ha paddocks. According to Norton (1998), this small-scale research station paddock precludes the opportunity to observe patch grazing effects in continuously grazed systems.

B. A paradigm that assumes that rotational grazing *per se* controls the level of defoliation experienced by individual plants

Norton (1998) cites multiple studies to demonstrate that the use of rotational grazing methods does not necessarily result in the defoliation of more plants than continuous grazing systems. He points out that higher defoliation rates are a consequence of higher stocking rates rather than rotational grazing *per se.* Therefore, implementing rotational grazing methods at relatively low stocking rates is unlikely to make any difference to agronomic performance at a paddock scale. Adaptive grazing management may achieve beneficial outcomes only when stocking rate achieves 100% defoliation over a short time frame.

Norton (1998) concludes that a scientific argument can be made for a rotational system of grazing to increase production, groundcover, and feedbase diversity so long as it concentrates livestock at (a) high densities for (b) short intervals. These two requirements support uniform defoliation at a moderate defoliation level across an entire paddock. It seems noteworthy that the rotational grazing systems employed by graziers in the present project agree that the practice conveys benefits only when it is linked with higher stocking rates to achieve brief periods of intense grazing. Figure 18 illustrates that a stocking rate of 20.76AE/ha achieved 100% defoliation of a Buffel Grass dominant pasture after a 24-hour grazing period at Property A (Rolleston).

Figure 19: Comparison of residual pasture biomass in a paddock after grazing for 24-hours at a stocking density of 20.76AU/ha (A) and biomass of the next paddock that will be grazed (B) (Property A: Rolleston).

As already mentioned in Section 3.2.2.1.1, a lack of empirical data for determining the optimal defoliation practices for the key pasture species used within the extensive grazing industry of Northern Australia may also explain why comparative grazing studies have not observed consistent differences between adaptive and continuous approaches to grazing management. It would seem difficult to formulate best practice adaptive grazing management for comparison with continuous grazing methods without this data.

Intriguingly, many comparative grazing studies conducted since Norton (1998) are not designed to address his criticisms. On the one hand, studies tend not to observe and report the percentage of plants defoliated over a specific time frame. On the other hand, constraints on the size of grazing area available for controlled grazing experiments on research institutes makes it difficult to observe potential long-term patch grazing effects within continuous grazing treatments.

3.2.2.2 Ancillary practices required for implementing adaptive grazing management

The implementation of the adaptive grazing management practices used by project participants requires ancillary infrastructure and management practices. These practices facilitate the operation of the grazing system and do not require verification from the peer-reviewed literature.

3.2.2.2.1 Fencing of paddocks

Practitioners who had implemented "time-controlled" grazing practices for > 5 years had an average of 47 paddocks/mob (range: 18-88 paddocks/mob) with an average size of 32 ha/paddock (range: 20-60 ha). The three practitioners interviewed on property reported that their fencing of paddocks aim to achieve a grazing intensity capacity of 20-60AE/ha. This high intensity stocking rate is critical for achieving a uniform and moderate level of grazing over a short time period (i.e. 1-4 days).

3.2.2.2.2 Water infrastructure

The large number of small paddocks is accompanied by an extensive high flowrate drinking water system. The average distance to water within paddocks for time-controlled grazing systems considered in this project was 729m (range: 400 – 1000m). This is significantly less than the < 1600m to drinking water recommended to optimise pasture utilisation (Holechek *et al*., 1995).

3.2.2.2.3 Livestock behaviour management

The three practitioners interviewed on-property emphasised that the successful implementation of their grazing systems relied on intentional livestock behaviour behavioural management. The key concern expressed by these people was that the regularly movement of livestock between paddocks must (a) not allow them to anticipate a move by standing at the gate and (b) lead them to run through newly access paddocks and trample pasture.

Property A (Rolleston): *Low stress stock handling practices are employed to mitigate the risk of regular paddock moves creating a negative impact on grazing behaviour and pasture utilisation.*

Property C (Baralaba): *The practitioner trains new mobs by mustering them to a closed gate using low stress stock handling. Once the gate is opened, they control livestock entry by forcing them to walk behind them into the paddock. The livestock are not permitted to roam freely until all heads are down grazing. This prevents animals from trampling pasture with the excitement of entering a new pasture break. Where possible new cattle are mixed with an experienced mob. Cattle can be moved from paddocks via two different gates, and this also prevents them from anticipating moves.*

Property D (Gogango): *To prevent mobs from anticipating moves, the practitioner visits paddocks at random times. New cattle are inducted by tagging/branding and via introduction to electric fence tapes.*

3.2.2.2.4 Grazing charts and livestock trading

The practitioners uniformly rely on historical grazing charts to inform decisions around carrying capacity and livestock trading. A grazing chart collects daily information that includes the number of livestock grazing each paddock, the length of time within the paddock, and rainfall. Over time this provides the practitioners with confidence around the number of stock grazing days (SDH) generated/hectare/100mm rainfall. These historical records allow this type of grazing system to anticipate:

A. The carrying capacity they can sustain after the initial "green date" (i.e. > 50ml rainfall in < 3 days at the start of the growing season).
B. The rate at which their carrying capacity will fall with declining rain.
C. The time to sell livestock.

It was common for the interviewed graziers to refer to a dry period rather than a "drought". Those interviewed regarded the notion of a "drought" as encouraging a grazier to identify as a victim.

> **Property A (Rolleston):** *The practitioner knows how much grass the property will grow by referring to the Grazing Chart data. This person indicated that a continuous grazing system is unable to refer to this kind of data to make stocking decisions.*
>
> **Property C (Baralaba):** *The producer explained that "if you haven't had a wet season by March how can you refer to it as a drought in the following December?" By referencing the Grazing Chart against declining rainfall this practitioner has already sold livestock before other producers who do not keep SDH/ha/100mm records.*

3.2.2.3 Adaptive grazing management for the achievement of viable and productive grazing PMLU on rehabilitated landforms

The adaptive grazing management practices described in this report may have relevance for the achievement of completion criteria for viable and productive grazing PMLU on sloped rehabilitated landforms. Before summarising the potential benefits this approach to managing these landforms may have for the mining closure process, it seems necessary to anticipate its potential criticism. As already acknowledged (Section 3.2.1.1.2), peer-reviewed comparisons of the environmental and production outcomes of adaptive and continuous grazing systems yield conflicting results. The following observations are intended to justify this report's recommendation for why further research is warranted to develop adaptive grazing practices for managing rehabilitated landforms.

First, the biophysical of rehabilitated landforms precludes the implementation of conventional continuous grazing practices. The critical requirement for retaining adequate groundcover on a range of fragile slopes seems to necessitate the consideration of agile and adaptive grazing management methods.

Second, this report accepts the explanation Norton (1998) offers for why many studies have not observed differences between these grazing methodologies (Section 3.2.1.1.2). On the one hand, the scale of these studies does not accommodate spatial variability that leads to patch overgrazing in continuously grazed systems. On the other hand, these studies overlook that rotational grazing *combined with optimal grazing intensity* is intended to achieve the desired agronomic outcomes rather than rotational grazing *per se*.

Third, comparative grazing studies are weakened by a lack of agronomic data for determining the right time and intensity of grazing required to optimise the growth and persistence of desirable plant species within Northern Australia's extensive grazing systems. This project has not identified peer-reviewed research that, for example, defines the most appropriate stage of regrowth to graze any of the major exotic or native grasses relied upon in the Bowen Basin. By contrast, within the temperate grazing industry, this information is known for species such as Perennial Ryegrass (Donaghy 1998), Kikuyu (Reeves and Fulkerson, 1996), Pasture Brome, Cocksfoot, and Prairie Grass (Ordóñez *et al*., 2021; Turner *et al*., 2006). The lack of this information for species used within extensive grazing systems makes it difficult to compare continuous grazing with a treatment that purports to grazing plants at the optimal time for encouraging regrowth or plant diversity.

Though further research is required for their application on sloped rehabilitated landforms, adaptive grazing practices used by interviewed practitioners may provide an opportunity for the servicing the achievement of grazing PMLU completion criteria:

A. Maintenance of groundcover on sloped land

If the mining industry is to rehabilitate as much grazing PMLU land as possible, it needs scientifically verified practices for maintaining adequate groundcover on sloped land. As a function of RUE, pasture growth rates are expected to decline with increasing slope. The adaptive nature of grazing practices described in this report would allow operators to adjust the timing and intensity of grazing activities to suit slope requirements. For example, it may be possible to develop a system that prescribes grazing height and timing relative to slope. The verification of this approach may also provide potential PMLU landholders greater confidence to acquire relinquished mining land.

B. Land stability

The potential for using adaptive grazing methods to stimulate root growth has importance for the stabilisation of surface materials on rehabilitated landforms. The development of this method requires further basic research to define the optimal time of defoliation for maximising root mass for the plant species used in rehabilitation.

During periods where landforms remain too fragile for the grazing of cattle, it may be possible to use small ruminants (e.g. goats) and/or slashing to achieve a similar agronomic outcome. The recent innovation of autonomous slashing vehicles could also have relevance for achieving this outcome on rehabilitated land.

Adaptive grazing management will also lessen the risk of erosion by maintaining groundcover and minimising the time livestock remain on rehabilitated sloped landforms. As observed on Properties C (Baralaba) and D (Gogango), this approach to grazing management increased water infiltration and decreased the turbidity of surface water.

C. Feedbase quality

The achievement of viable and productive grazing PMLU requires management that optimises feedbase quality. This report has presented evidence that adaptive grazing practices enable (a) the utilisation of pasture when it is of optimal nutritive value for livestock and (b) the provision of a competitive advantage to desirable plant species. It was noted, however, that the extensive grazing industry lacks empirical agronomic data for determining the appropriate time for grazing relative to plant regrowth to achieve these outcomes for desirable plant species used in Northern Australia.

D. Mitigation of the risks adverse weather pose for sloped grazing PMLU areas

The reliance of adaptive grazing practices on relatively small paddocks provides an opportunity for the strategic fencing of fragile slopes for the exclusion of livestock when these areas are relatively wet and at greater risk of mechanical damage.

3.2.3 Livestock production practices for achieving missional outcomes

Project participants implemented livestock production practices for the achievement of at least three missional outcomes.

3.2.3.1 Soil carbon sequestration

There was a commonly held view among the participants that their implementation of adaptive grazing management practices achieved higher rates of soil carbon sequestration than continuously grazed operations. This view assumes that if the benefits of plant recovery following grazing (i.e. stimulation of root growth) exceed the degradation that occurs (i.e. removal of above ground biomass), then livestock production will build carbon in topsoil (Teague *et al*., 2008). The participants in this project, however, had no historical soil carbon data to substantiate that their grazing practices were achieving reliable and consistent increases in soil carbon.

Though the sequestration of soil organic carbon and its long-term retention is primarily dependent upon local climate and soil clay content (McSherry and Ritchie, 2014; Mitchell *et al*., 2021), the superior ground cover evident on visited properties provides a potential indicator that they are sequestering soil carbon (Table 9). A relationship has been observed ground cover and soil organic carbon (Waters *et al*., 2019; Cork *et al*., 2012). At present, however, there remains insufficient data to determine if adaptive grazing practices are achieving long term and reliable increases in soil carbon. A consistent response in soil organic carbon (negative, positive, or negligible) has not been observed for any grazing method in Northern Australia (Bray *et al*., 2016). Though it remains possible that adaptive grazing practices informed by scientifically verified agronomic data could achieve higher soil carbon sequestration, confirmation of this outcome would require long term studies (Sanderman *et al*., 2015). This report refrains from recommending the use of adaptive grazing methods for achieving higher carbon sequestration rates than continuous grazing methods.

In addition to aboveground carbon sequestration, the strategic incorporation of trees within a silvopastoral approach has the capacity to build topsoil OM, improve pasture production within interrow spaces, and diversify revenue from its post-mining land use.[67] Jose *et al* (2019) explains that this kind of pastoralism aims to integrate economic benefits (e.g. income generation, revenue diversification, increased land value) with the provision of environmental services (e.g. soil enrichment, nutrient recycling, carbon storage, shade etc).

3.2.3.2 Remediating bare patches

The use of livestock to remediate bare patches, including those caused by exposed sodic subsoil was common among the interviewed practitioners.

[67] Note that a Rehabilitation Strategy document produced by one of this project's mining company partners recommends that disturbed areas be returned to grazing after it has undergone a process of considering other end-uses with higher economic value than previous use. The incorporation of dual-purpose trees within a silvopasture complements the latter objective.

The Practice: The practitioners use contouring, the concentration of livestock, and various machinery to promote the establishment of vegetation on bare areas:

- Contouring may be used to slow down water runoff and collect OM.
- Concentrating livestock on bare areas aids seedling emergence and establishment by disturbing crusted surfaces, depositing OM, dispersing seed, and facilitating the successional emergence of desirable plants.
- Machinery may be used to disturb and sow areas as well as slash less desirable successional plants to build soil OM.

Property A (Rolleston): *Considers weeds to be the gateway for establishing native grasses. It may be necessary to grow and slash weeds for 1-3 years to build up OM on scald areas. Encourages the use of feeding livestock molasses contain desirable seeds so that animals disperse the seeds on scald areas. This practitioner does not aim to establish the most desirable 3P species as the second successional stage. He prefers the use of hardier but palatable species (e.g. Secas). Where slashing is not practicable, it was suggested that goats could be used to manage weeds.*

Property B (Banana): *The producer has had success sowing Brassicas (Tillage Radish, Turnips, Chicory) into bare sodic soil patches to break up the soil with their deep taproot. The Brassicas are not grazed but allowed to rot back into the soil and build up OM to support future feedbase plant establishment. The areas are sprayed with herbicide prior to sowing with Brassicas. After the first year of using Brassicas, the operator has over sown the area with desired grass species (Bambatsi, Gatton Panic) and Desmanthus.*

Property C (Baralaba): *Concentrates cattle on bare patches to encourage the emergence of seedlings. Prior to rain, they encourage cattle to congregate on the focus area by covering it with hay bales. Once the livestock break up the capping, seed is sown over the area. They walk livestock slowly across this same area after rain. The practitioner may also apply a Yeomans plough at a shallow depth across the bare area and sow it with a "10 species seed mix." The producer does not mind if weeds dominate in the first season. After using the cattle to graze and knock over what grows post-sowing, they sow grasses and cereals in the second year. Livestock are provided access to the area when sown species seed to spread these to other areas requiring remediation.*

Property G (Baralaba): *Practices the strategic establishment of trees on ridgelines and sodic areas prone to erosion.*

Property K (Moura): *Works with voluntary weeds to remediate bare areas of exposed sodic subsoil. For example, he allows tap-rooted weeds (e.g. Roly Poly species) and Indian Cooch to establish first. The former weeds break up the soil to depth an increase OM. The latter rapidly spread across the ground and collect waterborne OM the next time it rains. Livestock are used to manage the weed phase, allowing for the emergence of more desirable sown species. This producer is in the process of installing small contour banks to change the water dynamics on his property and collect OM on bare areas.*

The principles: The common principles governing the practices the surveyed graziers implement to remediate bare sodic patches comprise the need to (a) break up a hard crust to allow the germination and emergence of pioneer plants; (b) facilitate improvements in soil OM to increase water retention; (c) manage a succession of vegetative stages as the gateway for establishing a 3P feedbase.

Scientific evidence: This project has not identified studies that evaluate the holistic approaches some of the practitioners used to remediate sodic bare patches. The benefits of disturbing the hardened crust overlying such areas for increasing water infiltration and seedling emergence have been demonstrated (Fox *et al*., 2004). The practices used to increase OM litter (i.e. covering areas with hay, slashing weeds) have also been shown to reduce hardening caused by rain drop damage, slow surface water flows to increase water filtration (Roth 1992) and increase soil porosity by promoting the activity of burrowing insects (Fox *et al*., 2004). Nevertheless, further research is necessary to validate and develop the holistic approaches these practitioners use to remediate scald areas.

3.2.3.3 Mitigating risks of a variable climate

There was general agreement among practitioners that their holistic silvopastoral approach provided greater resilience to a variable climate. They attributed a more rapid recovery following the cessation of prolonged dry periods to the following outcomes:

- Aligning the timing and intensity of grazing activities with pasture plant regrowth requirements (a) increased the size of root biomass and networks to draw on greater volumes of ground water and (b) this maintained higher levels of groundcover that increased rainwater retention and infiltration.
- A strategic use of trees modified the microclimate within paddocks that supported groundcover maintenance through dry periods and provided more optimal conditions for pasture recovery following the cessation of these periods.
- A biodiverse feedbase provided greater adaptability to varying climatic conditions.
- Overall improvements in soil carbon increased its water holding capacity.
- The use of grazing charts supported the making of confident livestock trading decisions to ensure that stocking rates match carrying capacity.

3.2.3.4 Management of tree regrowth

The practitioners indicated that their adaptive grazing practices facilitated a managed regrowth or establishment of trees. For example, Property A (Rolleston) pointed out that the exclusion of livestock from their paddocks for up to 350 days each year provided an opportunity for trees to regrow. This capacity for regrowth is not possible, according to this practitioner, within continuous grazing systems. Once strategic treed areas are established, the intensive grazing pressure these properties apply can suppress further undesirable regrowth. Scanlan *et al* (1996) has demonstrated that heavy grazing reduces the density of Eucalyptus seedlings.

3.3 Proposed silvopastoral model for remediating mining land

The project’s mining partners have expressed their preference for a scalable pastoral model for supporting the achievement of completion criteria for viable and productive grazing PMLU on sloped rehabilitated land and undisturbed land types within the Bowen Basin. To achieve this scalable outcome, this report proposes a silvopastoral model that draws upon the inventory of practices identified as remediating degraded grazing land within this region. The proposed silvopastoral model is intended for application on both broad categories of mining land:

A. Undisturbed grazing land

As discussed in Section 3.1.2.1, this land remains undisturbed albeit often degraded by historically suboptimal grazing practices. The beneficial outcomes of the approach's implementation on undisturbed land are generally the same as those that accrue to current practitioners in the Bowen Basin. Since these outcomes are already addressed in the establishment of inventory of practices used to remediate degraded land (Section 3.2), the benefits associated with implementing this model on undisturbed grazing land will not be discussed here. The next section, however, will address specific challenges that give rise to the model's application on undisturbed mining land.

B. Sloped land rehabilitated for grazing PMLU

The presentation of the proposed model in this section primarily relates to its implementation on land rehabilitated for grazing purposes. The recommended model aims to address the significant challenges reshaped spoil landforms pose for sequestering carbon and establishing a resilient feedbase that can support livestock production as a post-mining land use. As discussed in Section 3.1.2.2.1, the primary challenges for achieving this outcome include:

- erosion prone sloped landforms that may have exposed sodic and dispersive spoil materials where topsoil is lacking,
- poor moisture and nutrient retention owing to limited soil OM and poor soil structure,
- low relative humidity caused by poor hydrological features of spoil coverings and the elevated nature of reconstructed landforms,
- susceptibility of engineered topsoils to mechanical damage by cattle during dry and wet periods, and
- the successional establishment of a resilient palatable and species diverse feedbase on new landforms.

The silvopastoral model proposed for development here is schematically has the potential to overcome or minimise these challenges:

a. Under-utilised municipal liquid biowaste within the Bowen Basin is used to establish trees directly into spoil along regular contour lines and this frees up available topsoil for the establishment of pasture within interrow areas.[68]
b. The strategic layout of leguminous tree-lined contours improves inter-row growing conditions by increasing the relative humidity and decreasing soil and under-canopy temperatures.
c. Tree-lined contours reduce slope lengths, thereby decreasing erosive potential by reducing water flow velocity during rainfall events.
d. The regular layout of leguminous trees provides a uniformly distributed passive source of N input that supports long-term improvements in soil OM and moisture retention.
e. Dual-purpose trees lessen the demand on resources for livestock production by providing additional revenue streams for post-mining end-users. Microeconomic activity on rehabilitated landforms provides further opportunities for developing partnerships with local communities.

[68] Some mining companies may prefer not to apply topsoil on interrow areas to avoid introducing weeds.

f. Adaptive grazing management can support groundcover maintenance on slopes and optimise pasture root mass for improve soil stability.
g. The implementation of adaptive grazing management protects tree establishment, tree crops, assists in the prevention of weed encroachment, and lessens the risk of patch over-grazing and mechanical damage caused by cattle following rain events.
h. As a managed ecosystem, a silvopasture complements the need for the continuing monitoring and maintenance of a successionally developed feedbase on rehabilitated land. By establishing bioeconomic activity on rehabilitated landforms, operators will have a financial motivation for maintaining landforms well beyond mine closure.

The strategic incorporation of appropriate tree species within the proposed silvopastoral model aims to provide the following benefits for optimising environmental and production outcomes from rehabilitated landforms:

a. Trees can modify the microclimate within interrow pasture spaces by increasing the infiltration of surface water flow, water availability, reducing temperatures, and increasing relative humidity (McKeon *et al*., 2008; Alam *et al*., 2018; Jose *et al*., 2019).
b. Tree litter production and decomposition within inter-row pasture spaces can increase nutrient availability, capture of surface water flow, and reduce evaporative losses (McKeon *et al*., 2008; Helman *et al*., 2016).
c. The use of leguminous trees fixes soil N which stimulates biomass production, potentially leading to greater soil OM content.
d. Leguminous tree improvement of soil OM and deep soil drainage are associated with a reduction in soil ESP, pH, and increase soil microbial biomass (Wong *et al*., 2009).
e. Forage trees can be selected that provide additional digestible biomass for enhancing livestock production from rehabilitated land.
f. Dual purpose trees provide an opportunity to alleviate pressure on resources for livestock production by diversifying revenue streams for post-mining land use.
g. Improved animal welfare and production via the provision of shelter and shade
h. The sequestration of aboveground carbon in trees has the potential to more than offset livestock greenhouse gas emissions.

3.3.1 Silvopasture design, tree establishment, and tree species selection for rehabilitated landforms

This project recommends the development of an adaptively managed silvopasture strategically designed to reduce erosion, increase nutrient-recycling and carbon sequestration, diversify revenue, produce a more favourable microclimate for interrow vegetative growth, and improve biomass yield and productivity of sloped rehabilitated landforms. This management model aims to support the rehabilitation of as much grazing PMLU land as possible within the Bowen Basin. This project has not identified examples of mining companies implementing a strategic and scalable approach to silvopasture establishment on rehabilitated landforms within this region, though the establishment of tree-lined contours is observed at the Curragh Mine (Figure 20).

Figure 20: An example of tree-lined contour establishment at Curragh Mine (Google Earth 06/2016; -23.454539, 148.869129). Tree belts are approximate 8 metres wide and the distance between the edges of tree-lined contours ranges between 12-17 metres.

3.3.1.1 Silvopasture design

The proposed design for a silvopasture layout is basic and does not differ significantly from the conventional rehabilitation practices of alternating strips of topsoil with uncovered overburden benches or contours on re-shaped spoil dumps. Mines may already implement this approach to improve native tree establishment (i.e. limit competition from exotic grasses growing in topsoil) and provide shelter belts on land rehabilitated for grazing purposes. The spoil materials often used to cover reconstructed landforms lack pre-existing rootstock or seedbanks that can be used for managing the regrowth of trees on previously cleared undisturbed land. The need, therefore, to plant seeds or rootstock to reforest rehabilitated landforms provides an opportunity to incorporate tree species that contribute to a productive and intentional silvopastoral system and that may have commercial relevance outside of livestock production.

The silvopasture design elements are intended to complement the biophysical context of rehabilitated landforms.

A. Tree-lined contours are intended to reduce erosion by providing regular disruptions for water flow on rehabilitated slopes. The selection of commercially relevant trees provides a financial incentive for their maintenance which complements the requirement for ongoing rehabilitation maintenance.

B. Spacing between rows can be adjusted for slope gradient and perspective to optimise growing conditions of interrow pasture species. The silvopastoral system requires an architecture that minimises the potential for trees to suppress interrow pasture grown by competing for light, nutrients, and moisture (Scanlan 2002; McKeon *et al*., 2008; Helman *et al*., 2016; Hall *et al.,* 2020)
C. The tree-lined contours remain uncovered by topsoil, allowing for the more efficient spreading of stockpiled topsoil within interrow spaces (where desirable or necessary) for groundcover establishment.
D. The regular spacing of contoured tree lines and density of trees along contours aims to achieve a more favourable microclimate for pasture production and groundcover maintenance within interrow spaces (Alam *et al*., 2018).
E. The regularity of the design allows for the use of new and emerging digital technologies to optimise its management to achieve environmental, monitoring, and sustainable production outcomes.
F. The uniformly reduced light penetration could favour more desirable 3P grass species and legumes (Jose *et al*., 2019).
G. The planting of trees along contours permits the sparing use of municipal liquid biowaste and drip irrigation to de-risk the establishment process (see Section 3.3.1.3).

3.3.1.2 Silvopasture tree species selection

Though the implementation of a silvopastoral model on undisturbed grazing land will likely rely on the managed regrowth of native trees, when applied to rehabilitated land it may incorporate tree species that provide additional strategic benefits for livestock production as the targeted PMLU. On the one hand, the selection of suitable tree species will be determined by their ability to grow within the biophysical context of rehabilitated landscapes within the Bowen Basin (e.g. low rainfall, sodic soils etc). On the other hand, tree selection is determined by whether a species can contribute additional benefits within a silvopastoral system. Within this report, these additional benefits are categorised in terms of a tree species' capacity to fix nitrogen (i.e. leguminous), produce commercially relevant quantities of browsing forage, and/or diversify revenue from rehabilitated land.

To contribute to a profitable feedbase, a cultivated tree species needs to regrow a minimum of 1 tonne of biomass DM/hectare year^{-1} of greater than 55% digestibility to have commercial relevance for livestock production (LeFroy 2002). The energy requirement of a 450 kg weaner steer at maintenance is 50MJ ME/day.[69] To achieve this intake, the animal would need to ingest 6.7kg of 55% DM forage/day. Since this equates to a DM intake of 2.433 tonne/year, a forage tree plantation producing 1 tonne/DM year^{-1} of regrowth can support a carrying capacity of 0.41 AE/hectare which is at the upper limit of carrying capacities reported by project participants (i.e. 0.22 – 0.43 AE/hectare). It is significantly

[69] Calculations are based upon book values published in MLA, *Beef Cattle Nutrition: An Introduction to the Essentials* (Meat & Livestock Australia, 2015).

higher than the recommendation of Grigg *et al* (2000) that 0.14 AE is a satisfactory outcome for land rehabilitated for grazing purposes in the Bowen Basin.[70]

In Appendix 8.6, this report makes a primary recommendation of two leguminous trees for establishment within a silvopasture on rehabilitated land within the Bowen Basin, namely the introduced legume *Leucaena* and the native legume *Acacia victoriae* respectively. It invites secondary consideration of two additional native trees, namely *Pongamia* (oil production) and *Leptospermum polygalifolium* (Manuka honey production). Nevertheless, there remains scope for the incorporation of additional trees that suit specific biophysical contexts and social expectations for post-mining land use activities and productivity.

3.3.1.3 Silvopasture tree establishment on rehabilitated landforms

This report has already acknowledged that a topsoil deficit challenges the rehabilitation of mining disturbed land for grazing purposes in the Bowen Basin. Where insufficient topsoil is available, mining operations amend spoil with chemical and OM treatments. A lack of OM waste materials in the Bowen Basin results in mining companies paying a premium for these materials and limits the scalability of their application. There is simply not enough OM to cover the land area rehabilitated on an annual basis. The recommended approach seeks to minimise this challenge by using underutilised municipal liquid biowaste within the Bowen Basin to facilitate the establishment of tree-lined contours directly into spoil materials.

The potential for using OM to make spoil materials amenable for establishing vegetation is well understood (Wijesekara *et al*., 2016). Grant *et al* (2001) report that amendment with OM increases a soil's ability to sustain productive plant growth by improving soil characteristics such as water holding capacity, cation exchange capacity, structure, infiltration, and microbial activity are improved through the decomposition process.[71] The direct effect these biowastes have on spoils are to lower bulk density by increasing poor space and developing soil texture and they indirectly improve spoils by improving the chemical, physical, and biological spoil properties (Wijesekara *et al*., 2016).

This project has identified municipal liquid biowaste produced within the Bowen Basin as an underutilised source of OM (*c*. 100KL/day). The availability of this OM source has significance for the establishment of tree-lined contours directly into spoil materials. A recent study reported that the incorporation of municipal biowaste sludge into overburden at a rate of 60 tonne DM/ha significantly increased the successful establishment of trees directly into spoil materials (Spargo and Doley, 2019). Interestingly, Spargo and Doley (2019) observed that after two years post-planting, the tree canopy cover was 30% where plants were directed seeded into spoil amended with municipal biowaste compared with only 2% for trees established on spoil covered with topsoil. Though the biowaste improved conditions for plant survival in the spoil by causing a significant improvement in water retention, they attributed the main reason for the superior establishment and growth of trees in this

[70] Grigg *et al* (2000) used RUE to calculate that rehabilitated land in the Bowen Basin could support 32 x 400kg steers/200 hectares of rehabilitated land. The AE/hectare cited here converts these animals to 450kg steer equivalents (i.e. 450 kg steer = 1 AE).

[71] The present report is also aware of that the addition of OM to sodic spoils can potentially lead to an increase in the dispersiveness of clay particles (Wong *et al*., 2009). The application of OM to spoil as suggested in this report would require testing on small trial plots.

treatment to the absence of a seedbank in overburden that could outcompete tree seedlings.

Spargo and Doley (2016) speculate that lower OM application rates than 60 tonne DM/ha may have had the same effect on canopy coverage, though they caution that it may lower water retention in spoil. They determined that the water holding capacity increased by 30-50% in overburden amended with municipal biowaste and recommend that rehabilitation operations may observe similar results with application rates of 50 tonne DM/ha, though this will be dependent on the nature of the spoil materials.

The Isaac Regional and Central Highlands Regional Councils collectively produce more than 100KL of liquid biowaste/day. Assuming that this source of biowaste contains up to 15% DM (McCabe *et al*., 2019), this waste stream could contribute as much as 15 tonne OM/day for rehabilitation purposes. If we assume that 50 tonne OM/ha is required for establishing trees directly into spoil (Spargo and Doley, 2016) and trees are planted along 1-metre-wide contour lines 8 metres apart, the municipal liquid biowaste from these two regional councils could supply the necessary OM required to plant 2.7 hectares of trees/day. This equates to 986 hectares of rehabilitation/year within the Bowen Basin.

The advantages of using municipal liquid biowaste for the establishment of tree-lined contours on rehabilitated land are as follows:

A. Legislative requirements for the disposal of Municipal biowastes ensure that they meet environmental standards for metal contaminants (Australian Government, 2013; Spargo and Doley, 2016).
B. It can be concentrated on exposed spoil contours to achieve > 50 tonne OM/hectare, allowing for the economical use of available topsoil within interrow spaces.
C. There is an opportunity to build a synergy between municipal waste processing operations and rehabilitation operations. At present, Regional Councils spread liquid waste across drying pans prior to the handling of solids. The approach recommended here would likely involve councils providing liquid biowaste for direct application to spoils for the cost of transport (Isaac Regional Council. Pers. Comm).

Further work is required to determine optimal liquid biowaste application rates required for establishing various tree species in spoil.

3.3.1.4 Silvopasture interrow pasture and legume groundcover management

This project recommends the extension of adaptive grazing practices described within the defined inventory of practices for managing the maintenance and productivity of interrow pasture areas within the proposed silvopasture established on sloped reconstructed landforms. It is anticipated that the use of adaptive grazing management will be developed to facilitate the stimulation of root growth and groundcover, addressing bare areas caused by sodic soil-covered slopes, maintaining, and enhancing plant diversity, and mitigating the risks adverse weather events pose for fragile landforms.

This report does not seek to make specific recommendations on the selection of pasture grass and legume species for sowing within interrow spaces. A survey of participating mining companies revealed a uniformity around the selection of grass species (native and introduced) and legumes sown on land rehabilitated for grazing purposes. The inclusion of legume species within interrow pastures is critical for improving livestock production from tropical pastures. For example, Shotton (2011) reports that young steers grazing tropical grass pastures typically gained *c*. 150kg/year and that this increased to *c.* 175kg/year with the inclusion of legume companion species.

The definition of a productive feedbase as one that produces more than 1 tonne of available DM/ hectare year^{-1} of greater than 55% DM digestibility (Lefroy 2002) has implications for the use of Buffel Grass on rehabilitated land. Buffel Grass is a fast-establishing, deep-rooting, and highly water efficient tropical pasture species. Though it accumulates large quantities of biomass (e.g. 20 tonne DM/ha), Grigg *et al* (2000) observe that a relatively small quantity of this is annual growth (*c*. 2.8 tonne DM/ha). Two observations suggest that this pasture species may be less than ideal for achieving viable and productive grazing PMLU without the appropriate and intensive management achieved by graziers interviewed within this project:

A. Though it can achieve significant ground cover (i.e. 80%), a very low root basal area (i.e. 7.5%) may reduce its effectiveness at preventing surface erosion (Grigg *et al*., 2000). If it is to be used, Grigg *et al* (2000) recommend the inclusion of stoloniferous species within the initial seed mix to address this risk.
B. The dry matter digestibility of Buffel Grass falls from above 60% in the growing season to less than 50% during the dry season (Dixon and Coates, 2010). Where Buffel Grass is the dominant pasture species, livestock will not gain weight when DM digestibility falls below 55%.

There may be little mining operations can do to avoid the encroachment of Buffel Grass on rehabilitated land when stockpiled topsoil is spread across new landforms. Topsoil from most mining sites already contains large seed banks of this species, so that Buffel Grass is the first to establish when it is spread over spoil and its vigorous growth and drought resistance excludes native species (Erskine and Fletcher, 2013). The options for managing the challenge Buffel Grass may pose for rehabilitating land for grazing purposes seem limited to the following:

A. Operators could prevent its initial establishment by favouring the establishment of palatable native grass species by not spreading topsoil on rehabilitated areas. In the NSW Hunter Valley, Huxtable *et al* (2013) observed greater success sowing some native grass species into raw spoil compared to sowing them into replaced topsoil. They attributed this to exotic grass species outcompeting slower establishing native species on topsoil. The feasibility of sowing native grasses directly into spoil will depend on the availability of OM for amending these materials to support their germination and persistence.
B. If the efficacy of the adaptive grazing practices reviewed in the project can be verified, they should be applied for the management of Buffel Grass to optimise its nutritional value for livestock production and to encourage and maintain pasture plant diversity.

3.4 The "implementation gap" for scalable beef production as a rehabilitation service for re-commercialising mining land

The present project has undertaken to define the implementation gap that requires overcoming or minimising before the proposed silvopastoral model can be applied as a service for achieving viable and productive grazing PMLU on sloped rehabilitated landforms and servicing the remediation of undisturbed mining land. This report has examined the biophysical challenges these land types pose for implementing productive, profitable, and sustainable beef production. An inventory of practices used to remediate degraded land with success in the Bowen Basin has been itemised for application within a scalable silvopastoral model for managing mining land. The present section undertakes to identify and clarify the gaps in knowledge, practice, and infrastructure that may prevent the model's implementation. Research may be necessary to overcome or minimise these gaps prior to the implementation of the proposed model on this land.

3.4.1 Implementing the proposed silvopastoral model on undisturbed land and sloped grazing PMLU land

This project acknowledges the potential production and environmental benefits associated with adaptive grazing management that seeks to optimise plant recovery, ground cover, plant diversity, and groundcover. There remain, however, gaps in knowledge for its application on mining land.

3.4.1.1 Operational infrastructure

Extensive water and fencing infrastructure are required for adaptive grazing operations. Moreover, the initial establishment of tree-lined contours and/or belts on undisturbed and rehabilitated land will require additional fencing infrastructure to exclude livestock from juvenile trees and, potentially, drip irrigation. An interview with the Managing Director of a pastoral company owned by one of the partnering mining companies reported that a lack of fencing and infrastructure on rehabilitated land makes it almost impossible to achieve adequate grazing pressure for short periods. Furthermore, rehabilitation manuals used by partnering mining companies recommend that fencing is restricted to ridgelines to avoid erosion caused by livestock walking alongside these. Vehicular access may also be limited to ridgelines to reduce erosion. These restrictions impose a further challenge for implementing the regular movement of livestock through a series of relatively small paddocks to achieve the assumed benefits of adaptive grazing practices.

Interviews with graziers participating in this project revealed that they would not consider implementing their practices on leased undisturbed grazing land unless the mining companies invested in the required fencing and water infrastructure. To overcome this obstacle, this project recommends:

A. The development of a digital platform (i.e. integrated use of remote sensory data and virtual fencing) to overcome the obstacle of limited fencing for using adaptive grazing practices on rehabilitated landforms.
B. Collaboration with the coal mining industry to develop completion criteria for grazing PMLU that includes specifications for water and fencing infrastructure that support adaptive grazing practices.

3.4.1.2 Financial viability of establishing tree-lined contours on rehabilitated landforms

The proposed silvopastoral model incorporates tree-lined contours to achieve desirable production and environmental outcomes for rehabilitated landforms. Specifically, this element within the model seeks to:

- Mitigate the risk of erosion by providing regular biological disruptions for water flow and reducing wind speed.
- Enhance groundcover and interrow pasture production by creating a more favourable microclimate on elevated landforms and increasing nutrient recycling.
- Diversify revenue by supporting alternative mini-economic activities (Appendix 8.6).

The following gaps in knowledge and operational capacity prevent the immediate implementation of this element of the proposed silvopastoral model:

A. Carbon sequestration potential

The potential that silviculture has for sequestering carbon on historically cleared grazing land within the Bowen Basin requires further research. Gowen and Bray (2016) consider that this region has a significant opportunity for establishing regrowth carbon forestry. This assessment is based upon the region's recent history of land clearing and extensive grazing operations that have the potential for reforestation. The potential for managing regrowth from recently cleared land reduces establishment costs of planting tree stock, contributing to the financial viability for carbon forestry within the Basin. They cite bioeconomic modelling conducted by Gowen *et al* (2012) for a property within this region that anticipates that a carbon-cattle operation could be more profitable than a cattle-only enterprise.

Nevertheless, while carbon forestry has potential on undisturbed mining land, Australia's Clean Energy Regulator currently excludes the registration of carbon projects on land where rehabilitation is a legislated obligation. Further policy work is required to develop a potential for the livestock industry to access carbon markets through their servicing of rehabilitated landforms.

B. Suitability of commercially relevant tree species for establishment on rehabilitated landforms

The project has not identified studies that assess the viability of establishing the commercially relevant trees recommended for consideration in the proposed silvopastoral model (see Appendix 8.6). Given the cost of planting these trees, possibly using root stock, more research is required to understand their viability on these land types. Furthermore, it would seem important to consider a broader range of commercially relevant trees that can be incorporated to improve the model's scalability across a range of biophysical and climatic conditions.

Two of the project's three mining partners have expressed that they would not consider planting Leucaena on their land for environmental reasons (Appendix 8.6). Their concerns are legitimate and understandable. Nevertheless, this species offers the potential for significantly improving the feedbase on rehabilitated land, reducing enteric methane emissions of grazing ruminants, and generating new topsoil via its capacity to fix nitrogen. The livestock industry will need to provide evidence that specific management practices and cultivars are effective at mitigating Leucaena's invasive potential.

C. Production and nutritive value of forage trees and bushes for incorporation within a silvopastoral model for rehabilitated land

The project has recommended consideration of *Acacia victoriae* as a potential dual-purpose tree for incorporation within the proposed silvopastoral model (see Appendix 8.6). While the studies of Mor-Mussery *et al* (2016) demonstrate that this species can produce > 1 tonne/ha year^{-1} regrowth and is palatable for ruminants, there is a lack of digestibility data for this species or its lifespan when grown on rehabilitated land types. Before this species, and other suitable forage tree or shrub species are used within the proposed model they need to be examined for their potential to produce > 1 tonne/ha year^{-1} of > 55% OM digestibility.

D. Economic opportunities associated with commercially relevant trees

Further work is required to verify the economic opportunity of growing various commercially relevant trees on rehabilitated land. In addition to establishing the presence of a viable market and value chain, it will be necessary to consult potential landholders and local communities to assess their interest in supporting niche industries such as Manuka honey production, Wattle Seed harvesting, and Pongamia oil production (see Appendix 8.6).

E. Operational access to trees

Access to land within granted ML areas are heavily regulated by site management plans. People accessing the site to move cattle must have undertaken appropriate mine health and safety training and use machinery and vehicles that are certified for access to ML areas. While this may not prevent commercial grazing of rehabilitated landforms prior to mine closure, it is likely to create limitations for the harvesting of tree crops that rely on hand harvesting (e.g. Wattle seed). The challenge of operational access makes the use of a Manuka honey industry that relies on *Leptospermum polygalifolium* trees attractive because beehives can be situated adjacent to ML areas, making it unnecessary for operators to enter rehabilitated land (see Appendix 8.6).

3.4.1.3 Silvopasture design and establishment for productive, profitable, and sustainable beef production.

The optimal width of contoured tree lines and spacing between these relative to slope, aspect, and soil type for enhancing interrow ground cover and pasture production remain relatively unknown. This project has also recommended using municipal liquid biowaste for establishing trees directly into spoil. While the benefits of using OM to achieve this outcome are well understood, this project has not identified studies that recommend the rate of municipal liquid biowaste required for achieving tree establishment on rehabilitated landforms.

In addition to the layout of trees, it remains unclear what pasture species are best suited for establishment within interrow areas. Many minesite EAs require the presence of native pasture species on land rehabilitated for grazing purposes. It seems likely that the most appropriate species for sowing will depend on the layout of tree lined contours.

The mining companies express an interest in accelerating the time taken to introduce livestock onto rehabilitated areas. More research is required to develop grazing practices that stimulate the establishment of interrow pasture areas without damaging the relatively fragile land surface or destroying juvenile trees. In this regard, it may be possible to develop the use of autonomous slashing vehicles to achieve the same agronomic outcomes as adaptive grazing management.

3.4.2 Unknown agronomic features of desirable pasture species relevant for delivering environmental and production outcomes from adaptive grazing management

Though the project recommends the adoption of a grazing system that optimises plant recovery, groundcover, productivity, and plant diversity, it has acknowledged that the system's effectiveness is currently limited by a lack of agronomic understanding of desirable pasture species used within extensive grazing systems. The project revealed that practitioners observe specific grazing rules, but it has been unable to identify studies that inform the application of these rules within an extensive grazing context.

A. Removing livestock from grazing areas after 1-4 days

As already discussed, the practice of minimising the time livestock remain in a grazing area aims to optimise plant recovery by preventing cattle from grazing new regrowth. The need to remove livestock from pasture within prescribed timeframes to avoid slowing plant recovery is based on scientific evidence within intensively grazed dairy operations. For example, controlled glasshouse and mown scale studies were undertaken to inform paddock scale experiments when determining the appropriate time to remove livestock from s perennial ryegrass pasture (*Lolium perenne*; Fulkerson *et al*., 1994; Fulkerson *et al*., 1995). Equivalent studies have not been undertaken to determine the most appropriate (if any) time for removing livestock from native or exotic pastures grazed in the Bowen Basin. Since the regular movement of livestock is time-consuming, it seems important to establish if there are critical times by which cattle should be removed from paddocks relative to the desired plant species. It seems noteworthy that dairy cows can remain on Kikuyu (*Pennisetum clandestinum*) for up to six days without these impeding its rate of regrowth (W.J. Fulkerson. Pers. Comm). This species seems to remain resilient to livestock grazing new leaves for this length of time because of the large energy reserves held within this plant's stolons. There remains a need to understand how long livestock can remain on desirable pasture species used within the Bowen Basin without reducing plant regrowth potential.

B. Grazing pasture relative to regrowth phases

Interviewed graziers made decisions about when to graze a paddock according to its pasture regrowth phase. They recognise three such phases. Phase 1 applies to a paddock that is still recovering from a previous grazing. Phase 2 applies to a paddock that has recovered, has an optimal nutritional value, and is ready to graze. Phase 3 refers to a recovered paddock in which the oldest leaves have started to die. Ideally, therefore, the graziers aim to graze a paddock at the "top of Phase 2."

Whereas the intensively managed pasture-based dairy systems of Australia and New Zealand use "leaf-stage" to determine a paddock's readiness for grazing, this project has been unable to identify an objective method for assessing if a paddock has reached the "top of Phase 2" within extensive grazing systems. Though interviewed practitioners tended to regard the use of a "leaf stage of regrowth" as impractical in multifloral native pastures this has not been assessed under research conditions. Moreover, it seems unusual that a leaf-stage of regrowth has not been established for Buffel Grass dominated pastures. Researchers have established best grazing management practices for optimising productivity and nutritional value for other tropical grass species (e.g. Fulkerson *et al*., 1998; Boschma *et al*., 2016). These studies demonstrate that increasing the leaf to stem ratio of tropical grasses by regular grazing or defoliation significantly improves their nutritive value for livestock production. This project has not identified comparable studies for Buffel Grass pastures, but it seems likely that the same grazing management principles may apply. Further research is required to confirm this idea.

3.4.3 The effectiveness of adaptive grazing practices at increasing root mass

The inventory of practices compiled identified an opportunity for using adaptive grazing management to increase root mass for the purpose of (a) increasing soil stability, (b) supporting plant survival and responsiveness to rain during prolonged dry periods and (c) facilitating soil carbon sequestration. This project has not identified studies that assess the potential for strategic adaptive grazing management practices to achieve these outcomes within a semi-arid environment such as the Bowen Basin. If verified, the use of this grazing practice has importance for accelerating and maintaining the establishing of a resilient and topsoil building feedbase on sloped rehabilitated landforms.

3.4.4 Unknown potential for strategic grazing to increase biodiversity of grasslands

Practitioners interviewed within this project argue that a grazing system can be adapted to increase biodiversity within the feedbase. This project has acknowledged that the influence of adaptive grazing practices on encouraging and maintaining desired native pasture species within the Bowen Basin, especially within Buffel Grass dominated pastures has not been objectively assessed. Some anecdotal evidence for the importance of the timing of grazing for maintaining desired pasture species is provided by Wilson (1998). Though focussed on the influence of shade on pasture productivity, the method Wilson (1998) employed for estimating pasture yield by harvesting in May inadvertently reduced the proportion of Green Panic within the pasture from *c*. 80% down to 22% with a concomitant increase in the proportion of Rhodes Grass and weed species. Once it was realised that the May harvest weakened Green Panic's competitive advantage over other species, an earlier harvesting regime increased its proportion to approximately 90% over four years. More work is required to understand if grazing can be adaptively managed to support the competitive advantage of desirable species within extensively grazed pastures.

Several interviewed practitioners commented that they improve biodiversity by looking at what desirable species are present and then implementing a grazing regime that promotes the persistence of these species. While this method makes sense, there is little data to guide how desirable native plants should be grazed to provide them with a competitive advantage over less desirable grass species. This project assumes that this data will relate to time of season, grazing height, grazing interval, and their potential to withstand repeated defoliation relative to competing pasture species.

Finally, this project seeks to extend the practice of using livestock to disperse desirable plant seeds via faecal deposition to enhance plant diversity. The practicality and cost effectives of using an approach whereby livestock are offered licks containing the desired seed or grazing desirable pasture at seed to achieve this outcome requires further investigation.

3.4.5 Effectiveness of using livestock to remediate scald patches caused by sodic soil materials

It was common practice for the interviewed graziers to use livestock for targeted remediation purposes such as the renovation of bare sodic areas. The management of this challenge is of critical importance for the rehabilitation of disturbed mining land for grazing purposes. For example, EA's do not permit bare patches > 20m^2 or > 10m long down slopes. It seems necessary to undertake research that verifies and develops the practice of concentrating livestock on bare patches to stimulate germination, increase soil OM, and manage the successional development of a desirable feedbase. Moreover, this research needs to accommodate the reality of rehabilitated slopes that are more fragile than the bare areas address on undisturbed grazing land.

In addition to the missional use of livestock for resolving bare areas, the project has identified a need to develop an informed and intentional successional approach for managing an initial pioneer weed phase through to the establishment of a desirable and resilient feedbase. In this regard, it may be necessary to identify and define periods within a weed's growth cycle where it is palatable to livestock. This information would facilitate the use of weeds to provide soil stability while allowing a grazier to target the grazing of weeds to support the emergence of desirable successional plant species.

3.4.6 Confirmation of a business model for servicing the achievement of completion criteria for viable and productive grazing PMLU

Though this project anticipates a business model for livestock producers to service the coal mining industry, the following gaps in information need filling for its refinement:

3.4.6.1 Financial model for benefiting from carbon offsets and biodiversity gains realised by the proposed silvopastoral model's implementation

A financial model that allows livestock producers to benefit from achieving carbon offsets and biodiversity gains requires development. As discussed in this report, it remains difficult to anticipate the extent managed tree regrowth reduces or increases the productivity of pasture. To encourage lessees to manage the regrowth of tree belts using adaptive grazing practices, mining companies may need to compensate potential production losses via revenue or services realised through the sequestering of carbon offsets and improvements in biodiversity.

3.4.6.2 Acquisition and installation of infrastructure required for implementing the proposed silvopastoral model

Graziers interviewed within this project indicated that they could not justify investing in the water and fencing infrastructure required to implement adaptive grazing practices on leased land. The model will need to provide guidelines for the equipment and infrastructure mining companies will need to provide for the model's implementation on undisturbed land.

3.4.7 Adequate coaching and recognition of practitioners

While there are existing opportunities for graziers to receive coaching in adaptive grazing practices used for remediating degraded land, the management of rehabilitated landforms present unique challenges. To provide graziers with the confidence to manage the achievement of strategic outcomes for grazing PMLU land, it seems necessary to develop an educational program for coaching graziers on the management of these sloped landforms. In addition to equipping these graziers with the requisite skillset, mining companies may require their lessees to have certified qualifications for implementing silvopastoral management of rehabilitated land.

3.4.8 Pathway for the acquisition of relinquished mining land

A stakeholder survey conducted by Rolfe *et al* (2018) revealed an appetite for graziers to acquire relinquished mining land comprised undisturbed, rehabilitated, and non-productive areas. They identify further work that is required to clarify the pathway and caveats that will apply to the acquisition of this land. For example,

A. What is the process by which land is sold?
B. What ongoing liabilities apply to the new landholder?
C. What are the completion criteria for providing confidence that a mining company can relinquish its financial liability over grazing PMLU?
D. What unique skillset is required for managing rehabilitated landforms post-relinquishment?

3.5 Opportunities for overcoming the implementation gap using emerging digital technologies

New and emerging digital technologies provide an opportunity for the development of a digital management platform that (a) overcomes the identified infrastructure limitations for implementing adaptive grazing systems on mining land as well as (b) provides relevant data collection and outputs for ongoing monitoring and evaluation requirements for rehabilitated land. Discussed below, it is anticipated that the platform would use remote sensing to measure and assess biomass coverage, yield, species type, and quality to inform remote livestock management using virtual fencing collars. The metrics generated by this system complement those required for regular monitoring and evaluation of rehabilitated land. For example, remote sensing and on-animal sensors allow for the identification of patch overgrazing, erosion, fuel hazards, and weed encroachment.

The integration of virtual fencing collars within the platform will facilitate rehabilitation maintenance, the managed establishment of tree belts, and the mitigation of risks posed by adverse weather events on sloped land. For example, not only will it allow for the monitoring of erosion areas from which livestock should be excluded during wet weather, it provides remote functionality for excluding livestock from these areas during and after adverse weather events and minimises traffic traditionally required to move livestock.

A diagram of the basic layout of the proposed digitally enabled managed silvopasture for rehabilitated sloped land is presented in Figure 21.

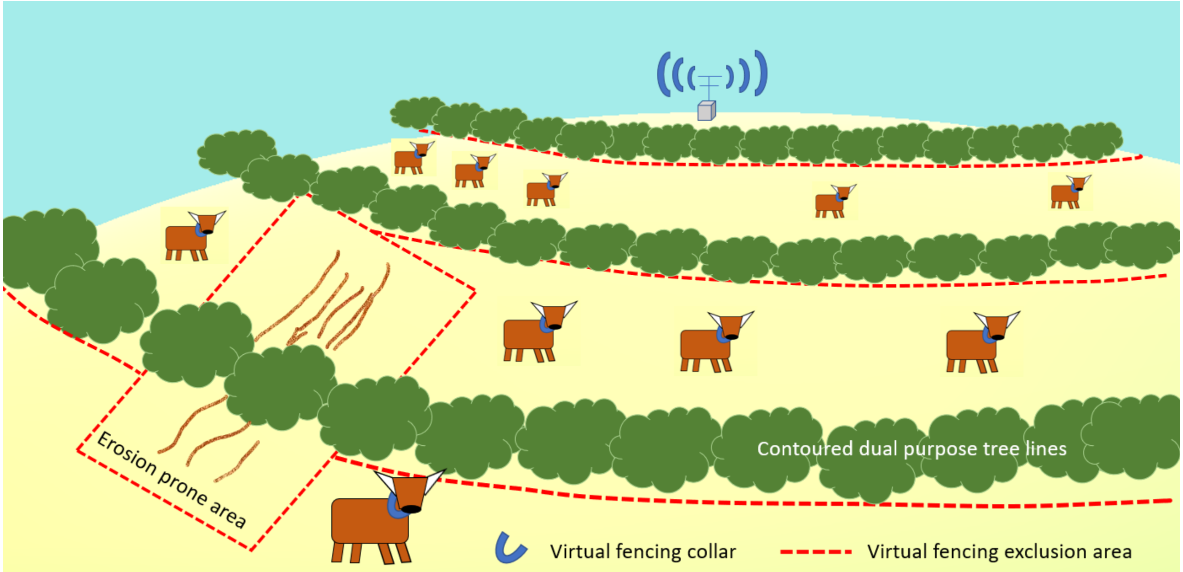


Figure 21: A digitally enabled silvopastoral approach for the achievement of grazing PMLU completion criteria

Though the use of these digital technologies may provide a means for managing the regrowth and grazing management of a silvopasture on undisturbed mining land, they have relevance for managing rehabilitated sloped landforms. This section primarily relates to the use of technology to manage grazing activities so that these achieve the environmental and production objectives of the proposed silvopastoral model.

3.5.1 Technical components for application within a silvopastoral system

The anticipated digital management platform relies on five technical components:

3.5.1.1 Remote on-animal tracking and sensing

This technology involves deploying sensors on livestock (most commonly a smart ear tag – Figure 22) to collect objective information on the location and behaviour of grazing livestock.

Figure 22. A smart ear tag allows the animal manager to understand animal location and behaviour and can help in making decisions about reducing grazing pressure in overgrazed areas

The data obtained from on-animal tracking and sensing can be used to detect where animals are and are not grazing to enable identification of underutilised and overgrazed parts of a paddock (Figure 23).

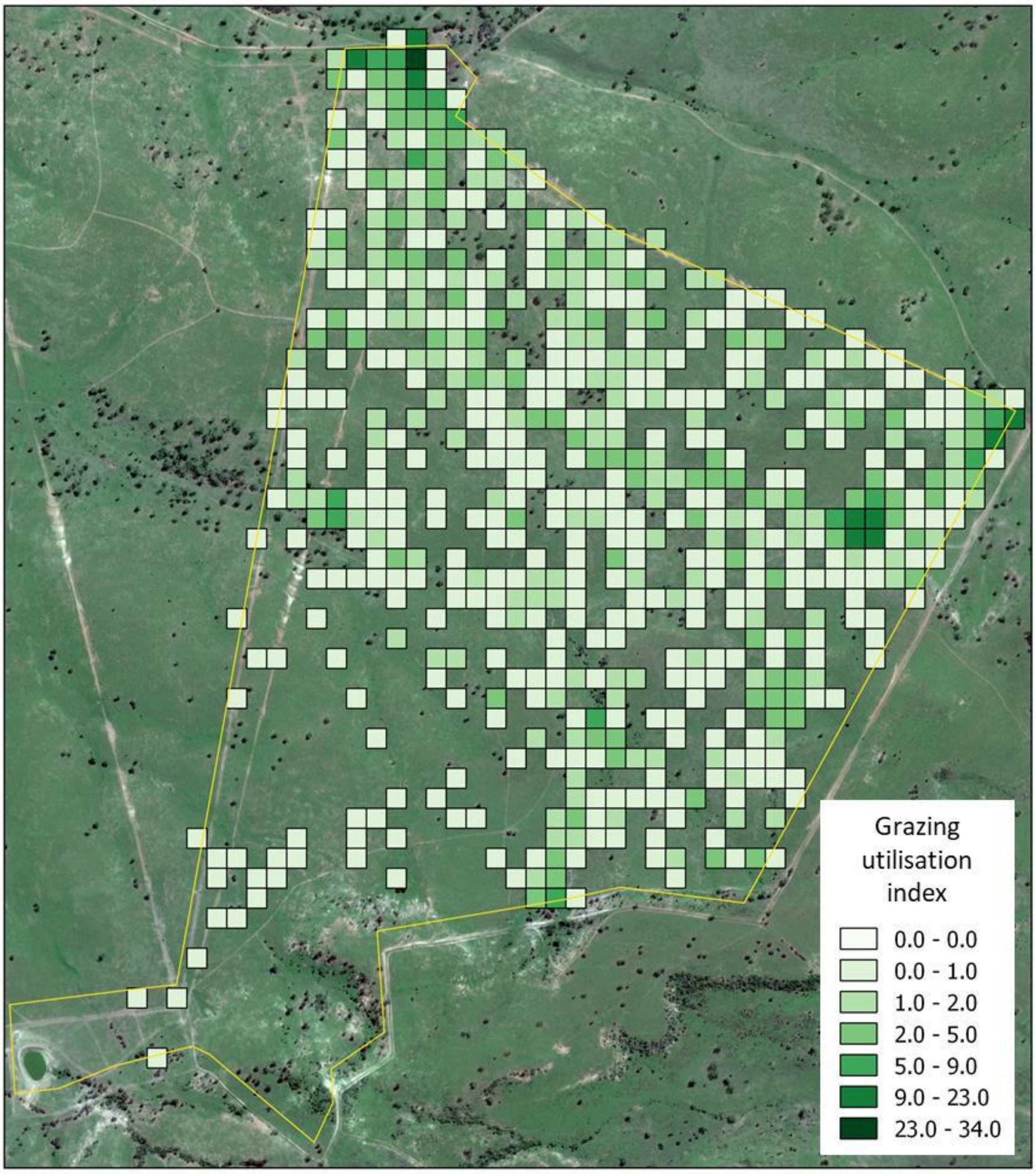


Figure 23. A grazing distribution map generated using on-animal GPS tracing devices. Highly used areas are at risk over overgrazing while underutilised areas may develop large amounts of unpalatably biomass. The objective data can be used to inform key decisions such as the implementation of virtual fencing boundaries.

To anticipate its contribution to a holistic digitally enabled grazing management platform for rehabilitated land, the grazing distribution map serves to:

A. Inform the use of virtual fencing that can reduce patch grazing or force livestock to graze on underutilised areas.
B. Provide objective monitoring data for demonstrating the achievement of viable and productive grazing PMLU.

3.5.1.2 Vegetation remote sensing and image analysis

The proposed platform will rely on the remote sensing of pasture availability and areas from which livestock should be excluded. Satellite technology is now commonly used to detect and quantify the condition of pasture within grazing systems. There are several applications for this data including management of ground cover for erosion reduction (Figure 24) and quantification of feed available for livestock, usually expressed and budgeted in terms of kilograms of feed per hectare (Figure 25).

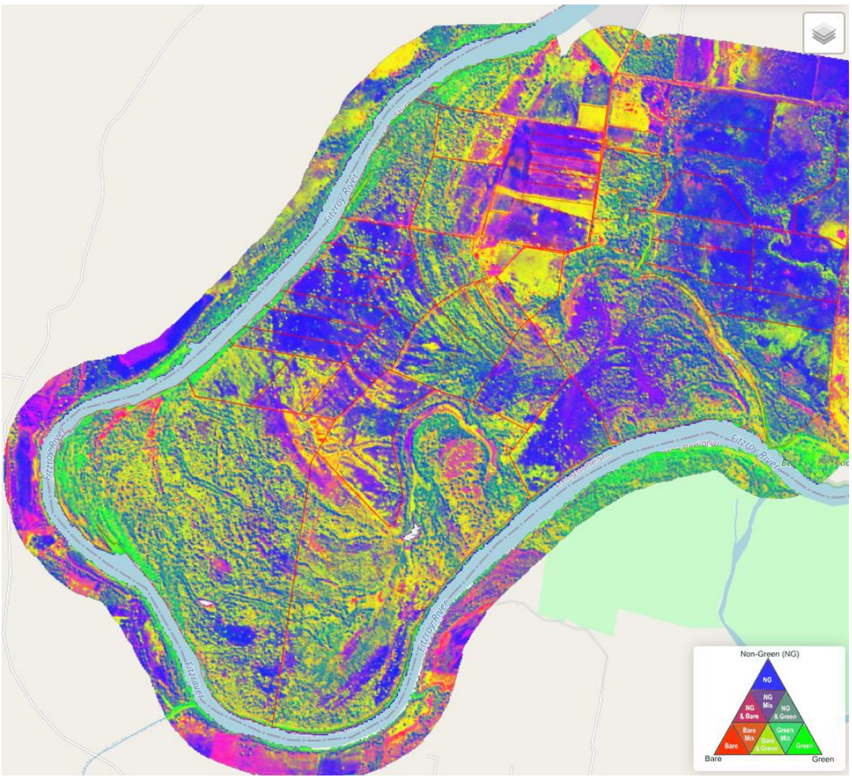
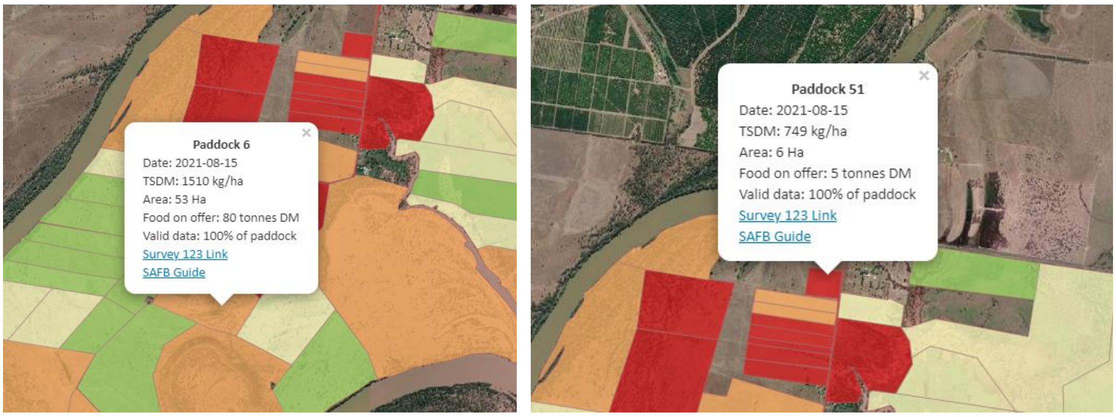


Figure 24. A Fractional ground cover image of a property, the red/orange/yellow areas have the highest proportion of bare ground and are at most risk.



A B

Figure 25. A paddock level biomass map generated from the Sentinel satellite system (source: Cibo Labs) showing a paddock with adequate feed of 1510kg/ha of Total Standing Dry Matter (TSDM) in A and a very low amount of feed (749kg/ha TSDM) in B. If cattle are allowed to continue grazing B it is likely to have significantly reduced animals liveweight gains as well as impaired pasture regrowth.

Both outputs may inform the adaptive grazing management of rehabilitated land. For example, the available standing dry matter could assist in determining when an area is ready for grazing without having a detrimental effect on root mass and soil stability.

The integration of remote sensing within the digitally enabled grazing management of a silvopasture will also enable land managers to set parameters for when livestock should be excluded from rehabilitated areas. For example, it seems likely that such a system could manage the presence and number of livestock on areas relative to slope, groundcover, and weather. This functionality will conceivably provide mining companies with a means for outsourcing the grazing management of rehabilitated landforms to demonstrate the achievement of completion criteria.

3.5.1.3 GPS-guided virtual fencing

Virtual fencing involves deploying a device on a grazing animal that controls its movements across the landscape (Figure 26). The system works by training animals to respond to an audio signal (a beep) which is delivered by a collar whenever an animal is approaching a boundary implemented within the system. The technology allows graziers to determine where and when animals can access certain parts of a paddock (Figure 27). Virtual fencing integrates with the on-animal sensor and remote sensing technologies to guide an animal manager to exclude erosion areas from grazing or temporarily reduce grazing pressure once certain biomass targets have been reached in vulnerable parts of a paddock.

Virtual fencing technology has additional applications for a silvopasture established on rehabilitated landforms. To begin with, it can be used to move animals rapidly off a landscape area that has become unstable due environmental conditions, for example when rainfall causes sodic soils to become dispersive. Second, virtual fencing has the capability for controlling grazing pressure adjacent to establishing tree lines. It is feasible that this technology might enable interrow grass control and limit tree browsing within a silvopastoral system. There are several commercial systems currently being evaluated across the industry, however some research is required to explore how these systems might be integrated in an advanced digital silvopastoral system proposed here.

Figure 26. Cattle fitted with a virtual fencing collar which enables the manager to control where these animals are allowed to graze and camp across a landscape.

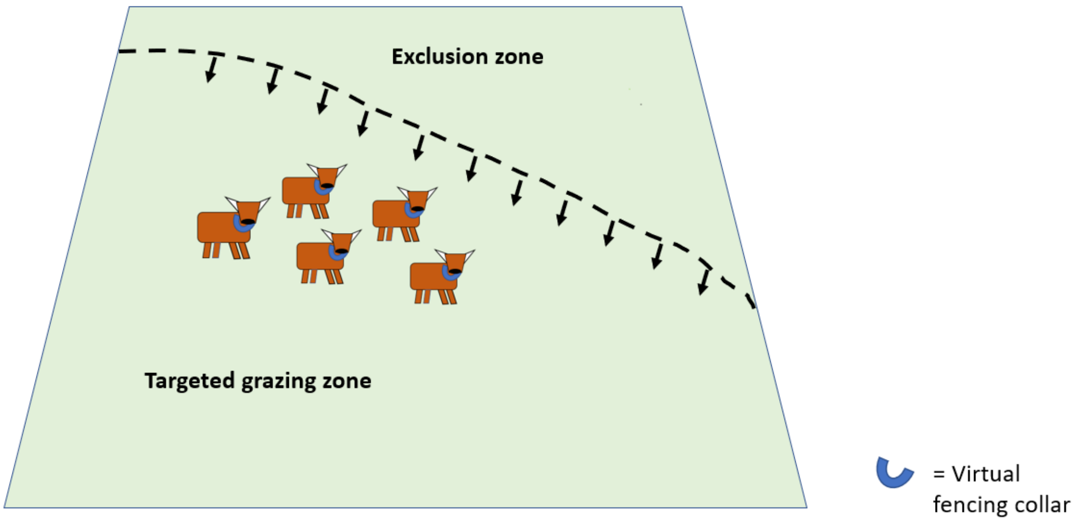


Figure 27. Virtual fencing collars enable the exclusion of livestock from remotely defined areas

3.5.1.4 Distributed weather and soil moisture sensors

As well as providing objective data on the location and behaviour of livestock and the pasture biomass, the proposed integrated system requires high resolution environmental data. High resolution weather data can be collected through spatially distributed rainfall and temperature sensors. There are two key applications of this information:

A. Rainfall data is required to predict spatial variation in pasture growth caused by storms, and
B. Real-time rainfall data can be used to identify when animals need to be removed from vulnerable areas.

Distributed soil moisture sensors enable decisions to be made around re-stocking areas when soils become stable again after drying out.

3.5.2 Specific applications of integrated sensor systems within the proposed digitally enabled silvopastoral approach

The proposed digitally enabled silvopastoral system integrates the previously described sensors and animal management systems to address several key issues in the establishment and maintenance of a silvopasture on rehabilitated land.

3.5.2.1 Remove livestock from high-risk areas within paddocks after significant weather events

Using high resolution weather station data will allow detection of rainfall events that might impact on dispersive soils. Where animals are found to be present (using on animal sensing) they can be rapidly moved away from these areas (Figure 28). This is achieved using virtual fencing technology which can direct animals away from vulnerable areas and, in the case of extreme weather events (e.g. flooding rains), move animals to weather appropriate grazing areas until paddock areas are deemed accessible. This degree of control can be achieved using current technologies and will enable vulnerable areas to be grazed to enable the stimulation of root growth, nutrient turnover, and improved stability.

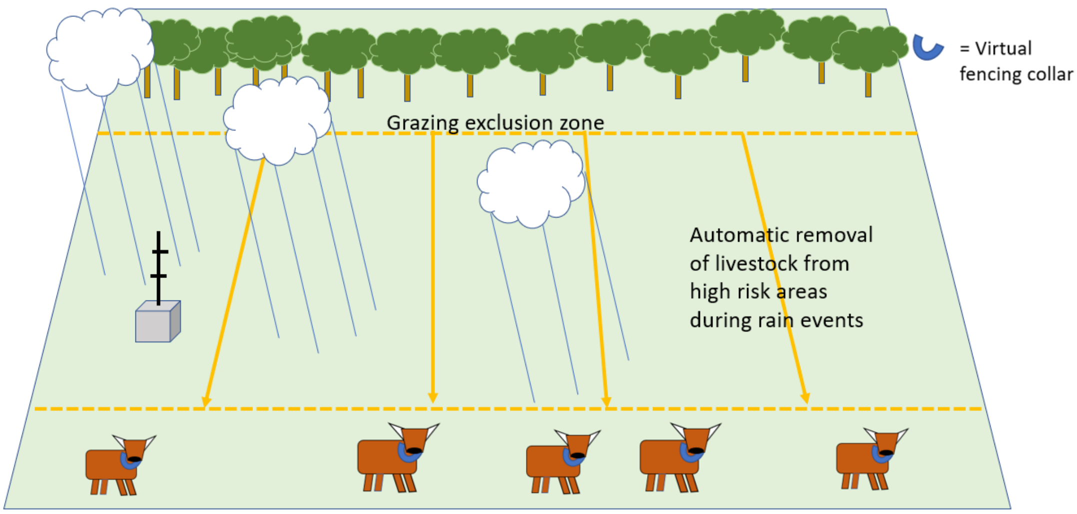


Figure 28. A digitally enabled system de-risks the potential for livestock to damage rehabilitated land during and after rain events.

This functionality aims to give mining companies greater confidence to allow livestock to graze newly rehabilitated areas to stimulate pasture root growth without damaging soils during rain events.

3.5.2.2 Maintain biomass coverage at appropriate levels for different slopes and soil types

Using integrated data from satellite imagery of ground cover levels along with historical animal tracking, predictions of grazing intensity can first be set and then implemented at a fine scale using virtual fencing. This differential grazing pressure will enable maintenance of variable biomass levels across rehabilitated areas. For some parts of a paddock, for example steep areas with shallow soil, only light grazing may be permitted to stimulate root growth while maintaining higher ground cover.

3.5.2.3 Manage pasture recovery following grazing

As discussed, one of the key principles of sustainable grazing practice and soil carbon sequestration is the use of adaptive grazing practices which provide plants with an opportunity to regenerate after grazing. Using virtual fencing areas allows for within paddock grazing at varying frequencies and, depending on the current plant species or the desired plant species, specified areas can be destocked for targeted periods of time. This capability may be particularly important where the establishment of diverse and native pasture species is desired. For example, the grazier has the capacity to focus grazing on an area of Buffel Grass to encourage the emergence of native grasses.

3.5.2.4 Exclude livestock from within paddock areas prone to erosion and scald

Remote sensing of soils and biomass, along with topography data can be used to detect current and emerging areas of erosion. Where appropriate virtual fencing can be used to restrict access of animals to these areas until they are remediated (Figure 29).

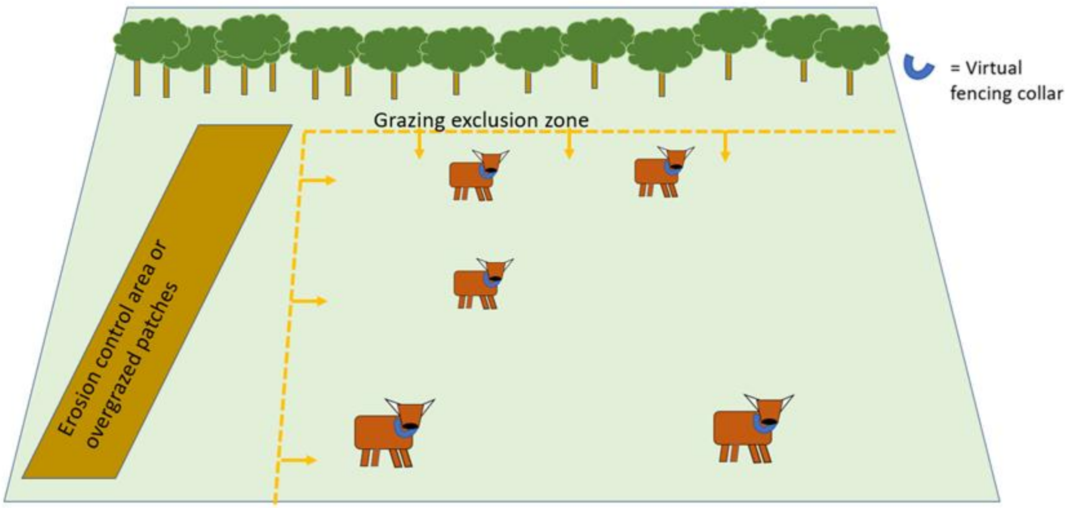


Figure 29. The proposed system can exclude livestock from erosion prone areas until they are resolved.

3.5.2.5 Targeted high impact grazing/camping to ameliorate degraded areas

The inventory of practices assembled within this report identified that bare patches can be returned to productive and stable landscapes through the targeted application of extremely high stocking rates. To achieve this outcome, animals are contained within a small area and the effects of trampling along with deposition of dung and urine provide a remediation effect. While this has only been tested using traditional electric fencing it is plausible that the same impact could be achieved with virtual fencing.

3.5.2.6 Manage weed encroachment and fire hazards

The ability to detect and quantify areas of weeds using remotes sensing can now be matched with targeted high impact grazing using virtual fencing (Figure 30). It seems conceivable that virtual fencing can be used to either (a) time the grazing of a weed infested area at its vegetative stage to reduce the potential for seed spread through dung or (b) target a window where weeds are palatable, providing a competitive advantage for desirable pasture species. The same technique can be developed to reduce fuel loads where fire poses a risk.

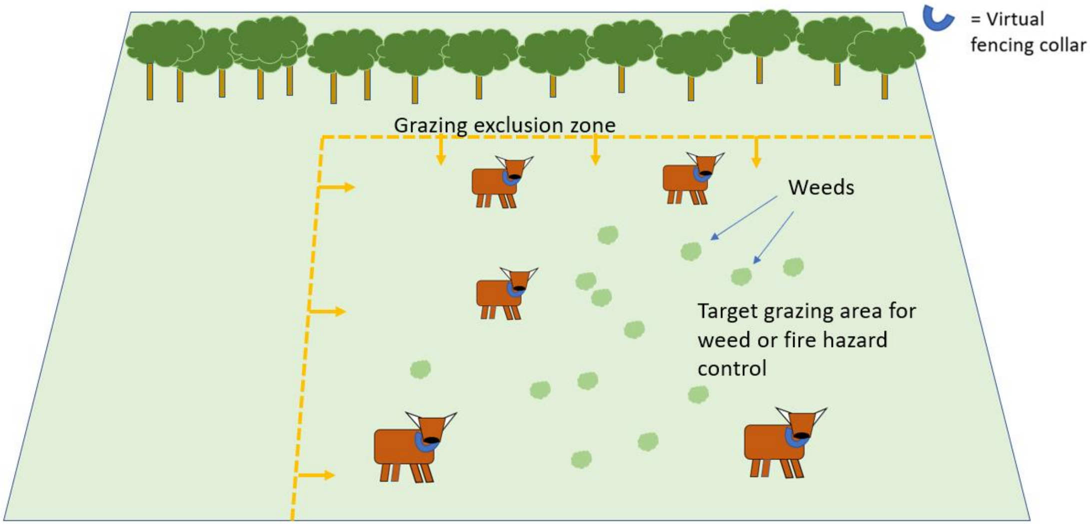


Figure 30. Virtual fencing can be used for managing the targeted grazing of weed and fire hazard control.

3.5.2.7 Protect silvopasture tree-line establishment by preventing cattle from browsing seedlings, disturbing drip irrigation infrastructure, and protecting tree derived revenue streams

One of the key applications of virtual fencing in the silvopastoral production system proposed here that it facilitates the management of grazing pressure on trees and the interrow pasture areas (Figure 31). While research is required to understand how these systems might be implemented, virtual fencing will enable fine scale management during both establishment and production phases of these landscapes. Virtual fencing could potentially be used to keep livestock from grazing trees during their establishment, allowing for the introduction of livestock to these areas earlier than otherwise possible. Grazing the interrow spaces would also reduce fire risk to establishing trees.

There is scope for using the digitally enabled management system to protect additional sources of revenue from trees. Animals could be prevented from browsing the trees using head position sensing technology which only allows grazing at ground level. Conversely animals could be managed to browse the trees when required. This system provides key flexibility in maintaining tree biomass for seed production or as a drought fodder store.

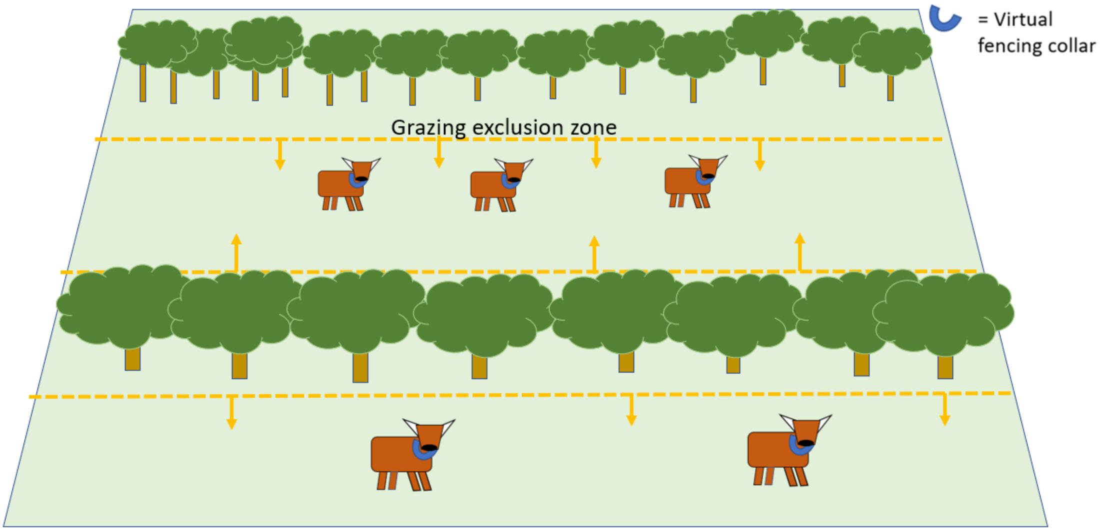


Figure 31. Virtual fencing can manage the grazing pressure on trees and interrow pasture areas within a silvopasture.

3.5.2.8 A managed ecosystem

In addition to the management applications described the interaction of sensor system will enable fine scale monitoring of landscape rehabilitation at a resolution not achievable using traditional techniques. A digitally enabled silvopastoral system essentially operates the rehabilitated landform as a managed ecosystem. It seems possible that it could generate regular reports on biomass coverage, yield, and utilisation by livestock.

E. Conclusion

This project has undertaken to define a pathway for the livestock industry to benefit from servicing the remediation of mining land within the Bowen Basin for productive, profitable, and sustainable beef production. The coal mining industry presently owns or manages about 770,627 hectares within this region, comprising 557,697 hectares of granted ML and 202,931 hectares adjacent to ML areas. Approximately 90% of this land was historically used for beef production. While livestock production continues unaffected on land held adjacent to ML areas, mining operations often exclude commercial grazing operations from most ML land. The exclusion of livestock from this land represents an opportunity cost of up to $60 million/year to the livestock industry, reducing the region's carrying capacity by about 111,000 AEU. The rate and quantum of this land that will become available for livestock production through the mine closure process depends upon (a) when underlying economically accessible coal measures are exhausted, (b) the achievement of completion criteria for rehabilitated land, and (c) the proportion of land disturbed by mining activities rehabilitated for grazing PMLU.

Potential exists for graziers, and especially perimeter landholders of mine sites to service the achievement of carbon sequestration, biodiversity, and general remediation objectives for the 202,931 hectares of undisturbed grazing land held next to ML areas. The financial benefits for delivering this service may derive from favourable agistment terms, the provision of essential infrastructure for supporting adaptive grazing management practices, a pathway to future ownership, and a sharing of revenue from carbon and biodiversity markets. Since the mining companies consulted within this project did not have formalised targets for carbon sequestration and biodiversity gains on this land type, an opportunity presents for the livestock industry to collaborate on defining realistic targets serviceable by livestock producers. A potential obstacle for delivering this service relates to the common practice mining companies have of leasing this land to previous landholders. On the one hand, these landholders may not have the skillset or interest for implementing practices that achieve carbon and biodiversity targets. On the other hand, mining companies may risk damaging important relationships with community stakeholders if they engage alternative land managers for achieving these targets. The project considers that the use of financial incentives and educational programs for certifying requisite skillsets for perimeter landholders may overcome r minimise these obstacles.

The coal mining industry is likely to disturb as much as 256,177 hectares of land through mining and exploratory activities in the Bowen Basin by 2050.[72] The project identified an opportunity for the livestock industry to contribute to the creation of as much grazing PMLU land as possible from the proportion of this area disturbed by open cut mining. The creation of grazing PMLU is challenged by the unique biophysical characteristics of reconstructed landforms in this region. These elevated landforms are characterised by steeper slopes than surrounding natural areas and are sometimes covered with erosive spoil materials due to a 30-50% shortage of topsoil relative to rehabilitation requirements. Mining companies consulted within this project indicate that there is a need to develop a scalable model for informing the landform design and management for viable and productive grazing PMLU. To achieve this outcome, the coal mining industry requires:

A. The development of scientifically informed and livestock industry supported completion criteria for sloped grazing PMLU land.

[72] Unfortunately, insufficient publicly available data exists to determine how much of this land will be disturbed by open cut coal mining as opposed to underground mining or exploration activities.

B. The expansion of current sustainable landform guidelines to include design principles that accommodate viable and productive livestock production on sloped reconstructed landforms.
C. The development of a scalable grazing management approach for achieving completion criteria for viable and productive grazing PMLU on sloped land.

By collaborating with the mining industry in achieving these objectives, the livestock industry stands to (a) benefit from increasing the proportion of disturbed land rehabilitated for grazing, (b) diversify revenue through the provision of services that achieve grazing PMLU completion criteria, and (c) contribute to the shaping of landforms and practices that support viable and productive grazing beyond mine closure.

To develop a scalable livestock management system for achieving grazing PMLU completion criteria and service the achievement of carbon, biodiversity, and production objectives on undisturbed land, the project surveyed graziers to assemble an inventory of practices successfully used to remediate degraded land in the Bowen Basin. Historical property data and the peer-reviewed literature were used to verify the efficacy of identified practices which were described under one of three practice categories:

(a) The strategic integration of trees within a silvopasture.
Using the Australian Government's FullCAM model to estimate carbon sequestration for a canopy cover of 20% achieved by establishing tree belts on the surveyed properties, the project revealed that this practice could offset between 68 to 296% of enteric emissions calculated from the self-reported carrying capacity.

(b) Adaptive grazing management
Interviewed practitioners adapted the timing, intensity, and length of grazing events to optimise plant recovery, growth rate, nutritional quality, and diversity. The surveyed properties and peer-reviewed literature produced sufficient evidence to suggest that adaptive grazing management led to improvements in SDH/100mm rainfall, groundcover, surface water quality, and land condition.

(c) Practices implemented for achieving missional environmental outcomes
Livestock were used to deliver specific outcomes such as the renovation of bare patches caused by the exposure of sodic subsoil, the managed regrowth of tree belts, and mitigating the effects of increasing climate variability.

The project has drawn on the assembled inventory of practices to propose a scalable silvopastoral approach for managing sloped grazing PMLU landforms. To summarise, the approach integrates the strategic use of commercially relevant tree-lined contours with the implementation of an adaptive grazing system that is responsive to plant growth requirements, slope, and weather conditions.

A consideration of the inventory of practices alongside the biophysical constraints of the two broad mining land types (i.e. undisturbed and rehabilitated landforms) was used to define an implementation gap comprising obstacles for the proposed approach's immediate implementation. These obstacles ranged from the lack of fencing and water infrastructure required for using an adaptive grazing system on mining owned or managed land, insufficient agronomic data to guide adaptive grazing management of pasture species used on rehabilitated landforms, a limited understanding for the optimal tree selection and silvopasture architecture for enhancing microclimate conditions and reducing erosion on sloped landforms, to an underdeveloped business model for its implementation. The project makes recommendations for the research and development required to overcome the identified obstacles.

Finally, the project has scoped the opportunity that new and emerging digital technologies provide for facilitating the implementation of silvopastoral practices on sloped rehabilitated landforms. It envisages the development of a digital platform that relies upon the remote sensing of groundcover, available biomass, weed incursion, and slope to guide virtual fencing facilitated adaptive grazing management of grazing PMLU. The development of a digital grazing management platform may extend beyond supporting the achievement of grazing PMLU completion criteria to include the servicing the remediation of undisturbed land.

5.1 Key findings

- Up to 770,627 hectares of mining owned or managed land within the Bowen Basin will become available, predominantly for livestock production through the mine closure process.
- 557,696 hectares of this land is currently held under granted ML and it is anticipated that 256,177 hectares of this land will be disturbed by mining activity and exploration by 2050.
- The mine closure process affords the livestock industry an opportunity to service:
    (a) The managed regrowth of trees on undisturbed areas to sequester carbon, deliver environmental services (e.g. improve surface water quality), and improve overall land condition by implementing adaptive grazing management practices developed for this specific context.
    (b) The creation of as much viable and productive grazing PMLU as possible.
- Graziers have already developed holistic silvopastoral approaches that deliver environmental services and optimise livestock production on degraded land within the Bowen Basin. This project has identified and defined an inventory of these practices that comprise the use of trees, adaptive grazing management practices, and the missional use of livestock to remediate specific problems such as scald patches.
- The implementation of the broad silvopastoral approach used by project participants on undisturbed mining land was considered business as usual. The core limitation, however, is a lack of the required fencing and water infrastructure required to support the use of adaptive grazing practices. The project anticipates that mining companies may finance the installation of this infrastructure or a digital grazing management system in return for the anticipated environmental services (i.e. building of carbon offsets, biodiversity, improved land condition). Nevertheless, considering that it remains uncertain to what extent the managed regrowth of trees may impair pasture production in different contexts, graziers may expect compensation such as reduced agistment fees or carbon credits that offset their operational emissions.
- The project used FullCAM to estimate that establishment of 20% canopy cover (using tree belts) of surveyed properties has the potential for offsetting between 68% (Middlemount) and 296% (Banana) of enteric methane emissions for their reported stocking rates respectively. The FullCAM model lacks data for making meaningful predictions for carbon sequestration on rehabilitated landforms, though at present mining companies are unable to access carbon markets for the reforestation of these areas.
- The project has proposed the development of a digitally enabled silvopastoral model for facilitating the creation of as much grazing PMLU sloped land as possible. The model

aims to address the specific challenges this land type presents for achieving viable and productive grazing PMLU. It recommends the incorporation of commercially relevant tree-lined contours that:

(a) Provide additional revenue to offset the qualified productivity of grazing PMLU land and to encourage the continued monitoring and maintenance of reconstructed landforms beyond mine closure.
(b) Serve as a biological disruption to slope length that reduces erosion caused by surface water runoff.
(c) Modifies microclimate to maintain adequate groundcover on interrow areas and optimise feedbase production.

The model anticipates the integration of adaptive grazing practices that:

(a) Facilitate ground cover maintenance and soil sequestration by stimulating root growth and optimising plant recovery, persistence, and diversity.
(b) Provide a tool for remediating problematic scald patches on sodic spoil covered slopes.
(c) Provide graziers with confidence to manage rehabilitated landforms parcellated within larger undisturbed land packages acquired through the mine closure process.

- The project obtained historical data from three exemplary properties that encouraged the view that their holistic silvopastoral approach was successful at remediating degraded land and optimising production and environmental services. Several observations were offered for why comparative grazing studies have reported conflicting results on the relative benefits of implementing the described adaptive grazing practices:

  (a) The project identified that the extensive grazing industry of Northern Australia lacks peer-reviewed agronomic studies that determine the most appropriate stage of regrowth and plant height to defoliate the most desirable pasture species used in the extensive grazing systems of Northern Australia. This information is essential for informing the right time to graze a pasture to favour the persistence and productivity of specific pasture species. Without this information, it seems that rather subjective views for the optimal management of pasture species govern what is a time-consuming practice of regularly moving livestock.
  (b) The size of paddocks used in many comparative studies does not accommodate the spatial variation in grazing patterns that may lead to patch over-grazing in continuously grazing systems.
  (c) Adaptive grazing management may yield some of its purported benefits only when stocking rate achieves 100% defoliation within a specific time frame. The length of the latter time frame has not been established scientifically for pasture species used in Northern Australia.

- New and emerging digital technologies were identified that could overcome many of the challenges a lack of fencing and water infrastructure present for implementing the proposed silvopastoral model on undisturbed and rehabilitated land. The development of these relatively expensive technologies into a digital grazing management platform within a mine rehabilitation context may provide an opportunity to innovate more affordable systems for the livestock industry.

5.2 Benefits to industry

The key benefits emerging from this project for the red meat industry comprise the following:

A. Partnership with the coal mining industry

The project invites further participation between the red meat and coal mining industries to collaborate on developing a silvopastoral model that (a) provides a pathway for creating as much grazing PLMU as possible and (b) services the achievement of mining company objectives for undisturbed and rehabilitated land.

B. Relinquishment of up to 760,627 hectares for grazing purposes

The project positions the livestock industry for contributing to the remediation of up to 760,627 hectares of mining owned and controlled for productive, profitable, and sustainable beef production. The exclusion of commercial grazing activities from most of the 557,696 hectares of granted ML within this area reduces the carrying capacity of the Bowen Basin by as much as 111,539 AEU. This project attempts to chart a pathway for the livestock industry to maximise the productivity and proportion of this area as it returns to livestock production through the mine closure process.

C. Creation of landforms that support viable and productive livestock production beyond mine closure

With as much as 256,177 hectares of largely grazing land expected to be disturbed by coal mining and exploration activities by 2050, the livestock industry stands to benefit from contributing to the development of scientifically verified completion criteria and landform design principles for creating as much grazing PMLU land as possible.

D. Social license

The model's implementation will position the livestock industry as change agent for reforesting significant areas of the Bowen Basin. The project's use of the Australian Government's FullCAM model predicted that all but one of the surveyed operations would more than offset their enteric methane emissions by achieving 20% canopy coverage through the establishment of tree belts on their properties. The development of the proposed silvopastoral model for implementation by the livestock industry may position it to market beef from the Bowen Basin as carbon neutral.

E. Business model for diversifying income via servicing of the mining industry

By validating the use of the proposed silvopastoral model for remediating mining owned or managed land, the red meat industry stands to benefit financially through the provision of environmental and rehabilitation services. It seems most likely that the financial benefits that accrue to the industry will comprise (a) affordable access to grazing land owned or managed by mining companies, (b) the provision of required infrastructure for supporting the model's implementation, (c) certification of carbon neutral red meat production by receiving this offset from a proportion of the carbon sequestered through the model's implementation.

F. Upskilling of graziers for managing grazing PMLU landforms

The project foresees a need to develop and educational program to certify a grazier's skillset for implementing a digitally enabled silvopastoral model that achieves completion criteria for viable and productive grazing PMLU. The training of graziers in the management of these landforms could have a multiplying effect, resulting in the model's implementation on much larger areas adjacent to mine sites in the Bowen Basin.

6. Future research and recommendations

The project identified the following research as required for developing and implementing a digitally enabled silvopastoral model for servicing the remediation of mining land in the Bowen Basin:

Landform design and completion criteria for viable and productive grazing PMLU

- Current completion criteria for grazing PMLU in the Bowen Basin were determined from ungrazed rehabilitated pastures and focus on groundcover, slope, and growth media properties. The project recommends partnering with the mining industry to define completion criteria that support viable livestock production on a range of sloped landforms (e.g. grazing days/100mm rain/ha y^{-1} relative to slope and spoil type; optimal canopy cover for supporting production). A set of scientifically verified criteria that are acceptable to the livestock industry will facilitate the acquisition of grazing PMLU for viable and productive grazing purposes beyond mine closure.
- Sustainable landform guidelines do not currently prescribe design principles for the creation of functional landforms for grazing PMLU. To achieve the creation of as much grazing PMLU land as possible, this project recommends that livestock industry collaborates with the mining industry to use newly developed completion criteria and best practice adaptive grazing management practices to inform the expansion of guidelines to include design principles for creating fit-for-purpose grazing PMLU sloped landforms. These principles are intended to optimise landform functionality to support productive, profitable, and sustainable beef production beyond mine closure.

Adaptive grazing management

- Controlled environment experiments to obtain data for defining the optimal defoliation practices are required to maximise the regrowth potential, persistence, and root mass of the main 3P species used within the Bowen Basin.
- Application of these studies for informing a commercial scale investigation within a mining context (i.e. both undisturbed and rehabilitated land types) of the benefits of using adaptive grazing management for achieving (a) optimal groundcover relative to slope, (b) increased productivity; (c) enhanced plant diversity, (d) resilience to dry periods, and (e) reduced erosion.
- The development of a digital grazing management platform for overcoming the unique challenges for implementing adaptive grazing practices on mining land types.

Silvopasture design and management

- Research may leverage the investment mining company partners already make in the establishment of trees on rehabilitated to understand the most appropriate species, planting densities, rate of municipal liquid biowaste application, and distances between rows relative to slope for enhancing interrow groundcover and pasture productivity. These studies will need to consider additional biophysical variables such as spoil type, slope, and perspective.
- Investigate the potential for using digital technologies to facilitate the establishment and management of silvopastures on rehabilitated landforms as well as the managed regrowth of silvopastures on undisturbed land.
- Research and develop the use of emerging digital technologies to adapt the missional use of livestock to remediate bare patches or manage weeds for application for addressing more critical issues on rehabilitated landforms.

Business model

- Collaboration with the mining industry to establish practical goals for carbon sequestration and biodiversity improvement on undisturbed and rehabilitated landforms.
- Investigate opportunities for overcoming some of the political or cultural obstacles for delivering services on mining land (e.g. grazing of undisturbed ML land: can it be done remotely using virtual fencing?)

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8. Appendix

8.1 Online Survey Questions

Defining the pathway for remediating mining land for productive livestock production

Project Overview

This project, jointly funded by Meat & Livestock Australia (MLA), Glencore, BHP, and Anglo American is being completed by Dr Leigh Trevaskis to guide the adaptation of a scalable livestock production system for partnering with the mining industry to provide environmental services and expanding sustainable beef production on historically degraded land under mining tenure. This survey aims to produce and inventory of practices pastoralists are using with success to remediate degraded land in Central Queensland. The survey will also be used to identify up to five pastoralists for on-farm interviews to gather a more detailed inventory of these management practices. The project will develop a strategy to remove the "implementation gap" that prevents the adaption of these practices to sequester carbon and build biodiversity for deployment on mining land.

Participation Procedure

You are invited to participate in an online survey which consists of questions that aim to identify and understand practices successfully used by pastoralists to remediate a range of different degraded land types in Central Queensland.

The project will use this survey to:

a. Create an initial inventory of practices that pastoralists successfully use to remediated degraded land in Central Queensland
b. Identify up to five pastoralists from different areas within the Bowen Basin for on-farm interviews that aim to gain a detailed understanding of how their operations have successfully remediated degraded land.

Completion of the survey will take around 10 minutes.

Benefits and Risks

There is no direct benefit to you for participating in this project. However, it is expected that this project may benefit the livestock industry by developing a business model for pastoralists to offer rehabilitation and remediation services to the resources sector.

Confidentiality / Anonymity

The survey collects your name, phone number, and nearest town for the sole purpose of building an inventory of practices used to remediate land within the Bowen Basin and identifying up to five participants for further interviews. Once surveys are received, your responses are de-identified prior to storage. After this time your responses will not be identifiable to you or your property.

Data will be securely stored for fifteen years in accordance with CQUniversity policy.

Outcome

The results of this research will be disseminated in the form of an MLA report, and potentially also in the form of journal articles and conferences.

Consent

Your consent to participate in this project will be obtained through your agreement to the Electronic Consent below.

Right to Withdraw

Your participation in this research survey is voluntary. You may withdraw at any time prior to completing the survey simply by closing the survey window on your web browser. If you wish to withdraw after submitting the survey, please contact Dr Leigh Trevaskis (l.trevaskis@cqu.edu.au; Ph: 0431058988) for the deletion of your survey response.

Feedback

A report on the larger project's outcomes will be available via MLA's website after June 2022.

Questions/ Further Information

If you have any questions about this project, please contact the Project Leader Dr Leigh Trevaskis via l.trevaskis@cqu.edu.au.

Please contact Central Queensland University's Research Division (Tel: 07 4923 2603; E-mail: ethics@cqu.edu.au) should there be any concerns about the nature and/or conduct of this research project.

This project has been approved by the CQUniversity Human Research Ethics Committee, approval number 0000023279.

ELECTRONIC CONSENT:

Clicking on the "next" button below indicates that:

- You have read the above information
- You voluntarily agree to participate; and
- You give your consent for the data you provide in the following survey to be used for the assessment and research purpose described above

Respondent contact details (Leave blank if you do not wish to be contacted):

Name:

Nearest town:

Ph:

1. **Farm layout and general operation**
    a. Predominant soil type
    b. Size of grazing area
    c. Number of cattle
    d. Number of paddocks/herd
    e. Predominant pasture species
    f. Forage tree and shrub species
2. **Grazing management:** Which of the following grazing systems best describe those implemented within your operation? You can select multiple systems.
    a. Continuous grazing
    b. Rotational resting (i.e. 2-3 paddocks/herd)
    c. Rotational grazing (i.e. 3-7 paddocks/herd; calendar based moves)
    d. Multi-camp (i.e. > 7 paddocks/herd; calendar-based moves)
    e. Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)
    f. Other [Please describe in the text box provided]
3. **Could you comment on your approach to designing the following aspects of paddock layout?**
    a. Size of paddocks relative to herd size (ha) [text box]
    b. Positioning of water points [text box]
    c. Fencing strategies [text box]
4. **Do you implement practices with a strategic objective to (select as many answers that apply):**
    a. Sequester soil carbon? Y/N
    b. Store above ground carbon in trees? Y/N
    c. Increase soil biodiversity? Y/N
    d. Increase above ground biodiversity? Y/N
5. **If you answered yes to any of (a), to which of the following categories do these practices belong?**
    a. Grazing plans
    b. Paddock layout and design
    c. Feedbase species selection
    d. Soil amendments
    e. Tree planting
    f. Other [Text box]

6. **What do you consider the most effective practice you have used for remediating degraded land?**

   [Text box]

7. **How have you measured the practice outcomes?**
   a. Farm productivity
   b. Paddock productivity (i.e. pasture yield, grazing days etc)
   c. Soil analysis
   d. Biodiversity surveys
   e. No measurements taken
   f. Other [text box]

8. **Have you introduced practices that diversify income streams (e.g. tree plantations)?**
   a. Yes. Please explain [Text box]
   b. No.

9. **How long have you implemented practices to sequester carbon or build biodiveristy?**
   a. 10 years
   b. > 5 years
   c. < 5 years

10. **How would you assess the state of your land prior to implementing these practices?**
    a. Good condition (Land Class A)
    b. air condition (Land Class B)
    c. Poor condition (Land Class C)
    d. Very poor condition (Land Class D)
    e. Varied. Please explain [Text box]

11. **How do you rate the state of your land now?**
    a. Good condition (Land Class A)
    b. Fair condition (Land Class B)
    c. Poor condition (Land Class C)
    d. Very poor condition (Land Class D)

12. **Do you have examples of remediated land that sit adjacent to historically degraded land (i.e. for visual comparison)?**
    a. Yes.
    b. No.

13. **Do you consent to researchers contacting you if they need to clarify any of your responses?**

8.2 Inventory of Practices: Survey participant responses and description of practices

Table 11: Biophysical context, strategic objectives, and data availability for surveyed properties

ID	Nearest town	Rainfall (mm)	Predominant soil type	Grazing area (ha)	Carrying capacity	Paddocks /herd	Strategic objectives	Practice categories for achieving objectives	The most effective practice for remediating land?	Data measurements	Land class pre-practice	Land class now	Examples of land to compare with un-remediated?
A	Rolleston	650	Loam	6781	1600 (0.24AE/ ha)	80	Sequester soil carbon; Store above ground carbon in trees; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design	Rest	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Biodiversity surveys (e.g. Biocondition scores)	C	A	No
B	Banana	686	Brigalow and softwood clay	2400	1000 (0.42AE/ ha)	15	Sequester soil carbon; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans, Paddock layout and design, Feedbase species selection, Soil amendments, Tree planting	Increasing water points and fencing into smaller paddocks	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Soil analysis	Varied (A,B,C,D)	B	Yes
C	Baralaba	714	Clay loam	2533	1000 (0.42AE/ ha)	11-15	Sequester soil carbon; Store above ground carbon in trees; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Feedbase species selection; Soil amendments; Tree planting; avoidance of artificial chemicals; re-seeding desirable species	Time controlled grazing and matching stocking rate to carrying capacity.	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Soil analysis; Biodiversity surveys (e.g. Biocondition scores)	B,C,D	B	Yes
D	Gogango	617	Sandy loam	3500	800 (0.22AE/ ha)	60	Sequester soil carbon; Store above ground carbon in trees; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design	Introducing rest	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Biodiversity surveys (e.g. Biocondition scores)	C	B	Yes
E	Dysart	614	Black soil	12672	2400 (0.19AE/ ha)	20-28	Sequester soil carbon; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Feedbase species selection; Soil amendments	Using rest to increase groundcover	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc).	B	A	No

F	Middlemount	558	Brigalow Scrub	19300	5000 (0.26AE/ ha)	Avg. 3			Rotational grazing, legumes and ripping		B	B	No
G	Baralaba	714	Sandy loam	5882	2000 (0.34/AE/ ha)	48	Sequester soil carbon; Store above ground carbon in trees; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Feedbase species selection; Soil amendments; Selective clearing (looking at what is growing under different species), Natural sequence farming, Yeomans water/nutrient injection.	Time controlled grazing	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Soil analysis; Soil carbon cores with Carbon Link	B and varied. Some country was farming country and very poor condition, which led to the change of practice and move to time controlled grazing.	A	Yes
H	Clermont	513	Loam	40500	13000 (0.32AE/ ha)	10	Sequester soil carbon; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Feedbase species selection	Herd impact and rest	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc)	B	A	No
I	Moura	599	Sodosol	1611	800 (varies) (0.5AE/h a)	23 (moving to 60+)	Sequester soil carbon; Store above ground carbon in trees; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Feedbase species selection; Soil amendments	Planning and controlling our grazing system and taking ownership of the inevitable mistakes.	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Biodiversity surveys (e.g. Biocondition scores); Photo monitoring of new pasture species and promoted regrowth	Land class C-D, depending on the paddock/ land type and prior management before we purchased it	B	No
J	Emerald	544	Heavy black soil to heavy sand	10000	800 (0.08AE/ ha)	7	Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design	Herd impact and then rest	Farm productivity; Paddock productivity (e.g. pasture yield,	Fair condition (Land class B);	B	Yes

										grazing days etc); Soil analysis	Poor condition (Land class C)		
K	Moura	599	Self-mulching black soil	12000	3-5000 (0.42AE/ ha)	10-45	Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design	High density grazing and rest specific for that area	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Soil analysis	B	A	No
L	Anonymous		Softwood scrub soil	1320	150-600 (0.45AE/ ha)	88 (total)	Sequester soil carbon; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Soil amendments	Rest	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc); Soil analysis, Minimal runoff into dams indicates improving water cycle	C	A	No
M	Thangool	686	Heavy black soil	2532	600 (0.24AE/ ha)	18	Increase soil biodiversity	Grazing plans; Paddock layout and design	Rest and specific timing of grazing.	Paddock productivity (e.g. pasture yield, grazing days etc); Soil analysis; Biodiversity surveys (e.g. Biocondition scores)	B	A	Yes
N	Miriam Vale		Clay loam	2500	1000LSU (0.4AE/h a)	30	Sequester soil carbon; Increase soil biodiversity; Increase above ground biodiversity	Grazing plans; Paddock layout and design; Feedbase species selection; Soil amendments; Tree planting	Paddock subdivision and water reticulation allowing greater intensity of grazing and longer rest periods	Farm productivity; Paddock productivity (e.g. pasture yield, grazing days etc),Soil analysis; Biodiversity surveys (e.g. Biocondition scores)	B	A	Yes

Table 12. Property layout, grazing system practices, and vegetation on surveyed properties

ID	Revenue diversification	Grazing system practice	Paddock size relative to herd (ha)	Water point strategy	Fencing	Predominant grasses	Predominant trees/shrubs
A	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	25-60	Wagon wheel cell design	Single electric	Buffel	Brigalow
B	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	60	One end of paddock	Small no. of paddock use the same water point	Buffel	Leucaena
C	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	Trying to minimise selective grazing and reach thresholds for density at 20 head/ha or	Centre of 4 paddocks to create square shaped paddocks for even	Single electric	Buffel, Bambatsi, Purple Pigeon, Blue Grass	Brigalow, Rosewood, Ironbark, Black Wattle

			60 head/hectare to stimulate nutrient cycling whilst ensuring productivity in stock (weight gains).	grazing and less than 400m walk to water.			
D	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	Aim for 20 head/hectare	< 1km to water	Fence to land type	Buffel	Brigalow
E	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	< 400	As many as possible, access in as many paddocks as possible	Electric, though barbed on heavy black soil where fences sink	Buffel, Black spear, Rhodes, Eurochloa, native grasses	Brigalow, Coolabah
F	No	Rotational resting (i.e. 2-3 paddocks/herd)	300	As central as possible within paddocks	Follow land types	Buffel and native species	Leucaena
G	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	We aim for average paddock size of 25ha for our current herd sizes. The stock density works out to be approximately 32 LSU/ha	Ideally placed so cattle do not have to walk any further than 800m for water.	Fence to land types to prevent selective grazing	Buffel, Eurochloa, Blue Grass, Spear Grass, improved pastures (Seca, Siratro, Wynn Cassia)	Eucalypt,Coolabah, Brigalow
H	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)		Centrally located	Barbed wire and some electric	Buffel	Leucaena
I	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	Depends on the availability of feed, the planned grazing system and what you're trying to achieve.	We try to ensure that cattle will not have to walk more than 500m to water. Troughs will be placed in open areas, away from trees, and in places with the least potential impact on riparian filtration areas.	Aware of soil type, vegetation, riparian zones	USA, Gayndah & Biloela Buffel, Purple Pigeon, Qld Bluegrass, Forest Bluegrass	-
J	No	Multi-camp (i.e. > 7 paddocks/herd; calendar-based moves)	As close to land type as possible (herd size does not matter)	< 2km apart	Smaller places all single wire electric three barb out west	Natives Flinders, Qld Bluegrass, Spear Grass	Wattle
K	Hardwood	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	Size of paddocks best reflects land type boundaries, thereafter distance to water	Logistically possible then distance to water then costings	Single wire within existing infrastructure	Buffel	Brigalow, Blackbutt
L	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	Paddocks vary from 3 to 30Ha. Herd size is not constant	800m – 1km apart	Land/soil type	Buffel, native species	Leucaena

M	No	Time-control grazing (> 7 paddocks/herd; pasture-recovery period determines moves)	country detimine paddock size and cattle numbers	Centre of paddock	Electric	Buffel	Leucaena
N	Hardwood	Multi-camp (i.e. > 7 paddocks/herd; calendar-based moves)	20-30ha average. 500+ LSU per mob	Not relevant within small paddocks	Single hotwire (remote monitored) Basically keep fencing off under-utilised areas until desired utilisation is reached.	Brachiaria, Blue Grass, multiple legumes, Black Spear Grass	Desmanthus

Table 13. Description of survey participant practices and support from the peer-reviewed literature

Practice	Sub-category	Description of practices/objective	Support from the peer-reviewed literature (I=inconclusive; Y=yes; N=No; NA=not applicable	Sample of relevant literature
General management	Strategic plan	• Framework that informs decision making to achieve strategic objectives.	Y	Fenster *et al* (2021)
	Adaptive	• The grazier adapts management to achieve pre-determined strategic objectives.	Y	Teague (numerous)
Attitude	Droughts	• Refuse to refer to dry periods as droughts. They prefer to manage stocking rates in anticipation of significant changes in carrying capacity. • Better off having no cattle when there is no rain so that retained groundcover captures water when it begins to rain again. • Prioritise ground cover. There is a dry season before a dry summer. Therefore, graziers have time to plan by matching stocking rate with carrying capacity.		
Grazing system	Time-controlled	• Stocking to carrying capacity • Flexibility/adaptiveness • Ground cover remains stable, stock numbers go up and down • Sometimes use a lead-follower system to priorities the ingestion of the best grass by growing cattle. Older cattle are used to graze more lignified grasses left behind by weaners. • Cattle remain in the paddock for between 1-5 days. • Readiness for grazing determined by the growth phase. Phase 1: Plants are recovering; Phase 2: Plants have recovered; Phase 2: Plants begin to senesce. Time control grazing aims to graze pasture at the end of Phase 2. • They monitor livestock faeces to determine if they are grazing at the correct stage of regrowth: Poor structure reflects that they are grazing pasture before Phase 2. Overly solid/woody reflects that they are grazing in Phase 3. • Rank paddock feed from 1-10 (10 = best) and adapt movements of cattle to these paddocks accordingly. • 30-60 days rest during the growing season. • Up to two grazing bouts/paddock over the dry season, leaving 30% of DM behind. Therefore, during the growing season, the rotation is determined by how quickly paddocks reach the top of Phase 2. During the dry season the feed budget determines when paddocks are grazed.	I	Compare Teague (numerous); Hulvey *et al.* (2021), Kleppel (2020), with Schatz *et al*. (2020), Hall *et al*. (2014), Tracey and Bauer (2019).

		• Goal of rapid rotation is to manage lignification of grasses. • Some operators ensure a paddock receives 60 days rest at the beginning of the growing season to allow roots to grow and support recovery from grazing over the rest of the growing season. They may graze every 30 days following this initial rest. • They may split mobs to utilise the best new pasture growth when paddocks are growing too quickly for one mob.		
	Multi-camp	• The operator uses calendar-directed moves of livestock every 14 days during the wet season. • Cattle remain within a paddock for 30 days during the growing season. • A 120-rest period is applied to paddocks in the dry season. • allows us to move them every six months. 2 week move in summer.		
Livestock management	Behaviour	• New cattle are often inducted new cattle via tagging/branding. Regular random visits to paddocks prevent livestock pre-empting paddock moves and running toward gates.	I	Unavailable
	Trading	• The participants use trading to maintain groundcover.	Y	Hunt (2008)
	Feed budgeting	• Ensuring that the stocking rate matches carrying capacity. • SDH/100mls allows the use of a grazing chart to anticipate when livestock need to be sold and this typically allows operators to sell animals ahead of the market trend. • Cattle are bought or sold in response to each feed budget.	Y	Hunt (2008) and importance of sustainable pasture utilisation.
	Stimulating root growth	• They use grazing to stimulate root growth as the engine room for sequestering soil carbon.	Y	Wilson et al. (2018); Teague et al. (2008)
Property layout	Paddocks	• Time controlled grazing: Paddocks small enough to ensure cattle fully utilise pasture within 1-2 days. • Multi-camp grazing: paddocks designed to have enough pasture for the calendar set grazing period. • Fence according to land type and slope so that uniform grazing pressure is applied across paddocks. • Electric tapes may be used to split paddocks when even higher grazing pressures are required to favour native grazes over Buffel Grass.	Y	Well-established within dairy industry studies.
	Water	• Increasing the number of water points reduces the walking distances for cattle and increases the area of land utilised by cattle. • The investment in fencing aims to get the value out of the more expensive water infrastructure.	Y	Holechek et al. (2004; Hunt *et al*. (2014)
Feedbase	Establishment	• Manage grazing pressure to encourage establishment of native species from pre-existing seedbank.		
	Biodiversity	• Overcome nutritional limitations of Buffel Grass in the dry season by encouraging emergence of more palatable natives at this time. • Motivated to encourage diversity in pasture species to mitigate the risk of "pasture dieback".	Y	Hunt (2008); Landsberg *et al*. (2014)
	Strategic rest	• Rested to encourage recovery from last grazing and to support the emergence and maintenance of desirable native plant species. • Prioritising rest to encourage and maintain desired native species.	Y	Bowman *et al*. (2009)
	Amendments	• At least three project participants are using Johnson – Su compost as a soil amendment to increase soil biodiversity. • The compost is either applied via liquid injecting, spraying seed coating, or as a dried additive to a trickle box with seed.	I	Unavailable
	Trees	• Changing relative humidity increases pasture productivity • Trees deep roots allows for mining of deep minerals that are deposited on soil via leaf litter.	Y	Alam *et al*. (2018); Jose *et al*., (2019)

Trees	Thinning	• Tree canopy cover from 20-to 40% helps improves growing conditions. Keeps the land cooler in summer and warmer in winter. • High density grazing applies browsing pressure on suckers/seedlings and this prevents further thickening. • Anecdotal evidence of tree canopy favouring more palatable grass species.	I	Belsky *et al* (1993). More information is required to determine when livestock production is impaired by increasing canopy cover within the Bowen Basin.
Bare patch resolution	Transitional plants	• Work with deep tap rooting weeds and cooch grass. The former break up the soil, the latter fills in the gaps. The process captures water and OM that will encourage the emergence of more desirable plants. • Intentional seeding of tussock grasses across bare patches.	I	Unavailable
	Livestock	• Concentrate cattle on bare patches. • Spread hay on bare areas to encourage livestock traffic on the area to break up the ground and distribute faecal matter. Spread seed after they leave. • Graze seeding pastures immediately before concentrating cattle on bare areas. • A lick containing desirable plant seed is sometimes offered to livestock before they are walked across scald areas. • Walk livestock through bare patches following rain.	I	Unavailable
	Mechanical intervention	• Contours facilitate capturing of water and OM ("leaky weir" method) • Use of a Yeomans plough to break the surface before re-seeding.	I	Unavailable
	Tree emergence	• Trees are planted or permitted to regrow in strategic areas to slow down water and drop OM. • Increase above ground carbon sequestration • Some operators push trees over scald patches to encourage OM retention and the emergence of plants.	Y	Moreno *et al.* (2005); Ryan *et al.* (2015);
Land rehydration	Contouring	• Installation of "leaky weir" contour banks to slow down water and increase its retention in the soil.	I	Unavailable
	Increasing groundcover	• Interviewed graziers commonly argued that their properties experience more rapid biomass growth following droughts because their ground cover reduced water run-off.	Y	Döbert *et al*. (2021); Silburn *et al*. (2011)
	Reducing bulk density	• Resting paddocks after intensive grazing to allow for soil to recover and increase porosity for water infiltration.	Y	Southorn and Cattle (2004); Sanjari *et al* (2008)
Riparian zones	Management	• Though fenced off, some operators still graze these areas. They use the fencing to avoid livestock entering riparian areas when it is too wet.	Y	Bailey *et al.* (2011)

8.3 Disturbance of land by underground longwall mining and its implications for livestock production as a post-mining land use activity

An underground coal mining method referred to as longwall mining is used to extract coal seams where financial or environmental considerations make it infeasible to use open cut methods. Longwall mining is conducted in a way that plans for the progressive subsidence of overlying land as the operation removes panels from underlying coal seams. The method extracts coal by shearing 1.6-3.9M high and approximately 250 – 300M wide panels through coal seams > 80M under the ground level. Multiple longwall panels may operate in parallel, separated by unmined pillars (35-80M wide) (Figure 31).

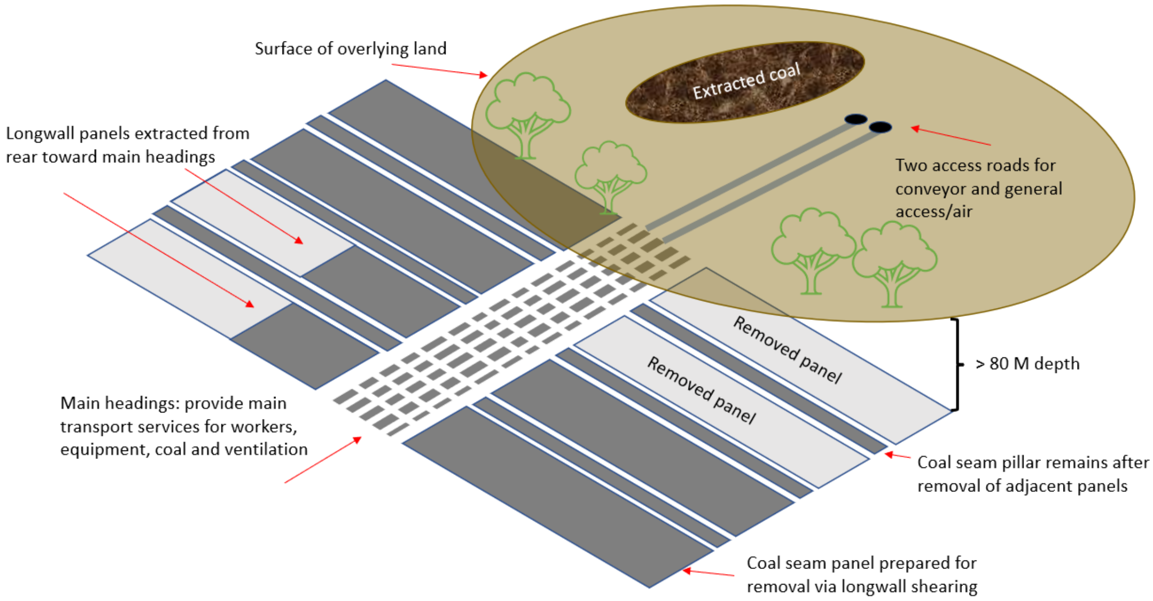

Figure 31: Schematic representation of a longwall mining operation layout

Once the tunnelling of roads ("headings") for access and ventilation are complete, 250-300M wide longwall mining systems are installed to begin coal extraction from pre-defined seam panels. A hydraulic support within this system prevents the collapse of the overlying land while the coal face is extracted and removed above ground via conveyor belts. As the mining operation progresses, the hydraulic support machine incrementally steps forward, allowing the overlying materials to collapse behind which is associated with land surface subsidence (Figure 32).

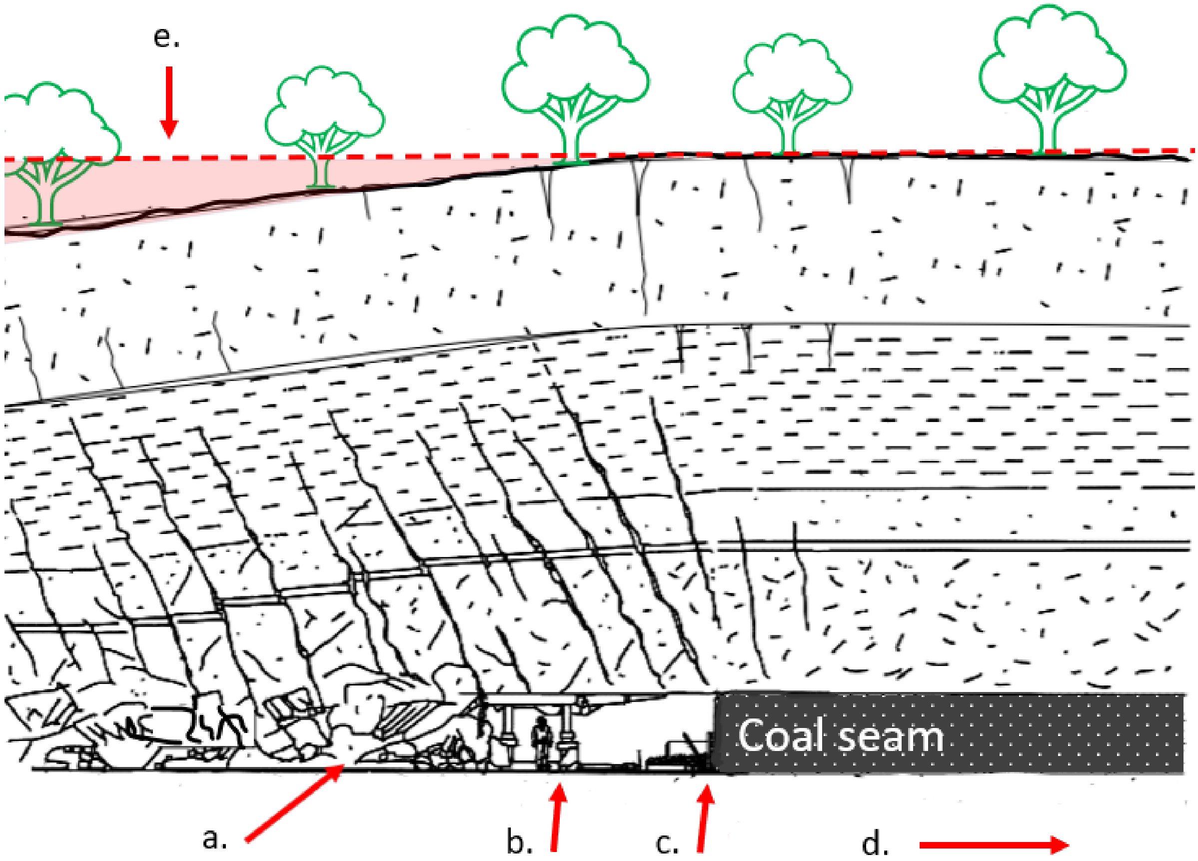

Figure 32: Cross section of a longwall mining operation illustrating planned subsidence. (a) Planned collapse of overburden behind hydraulic roof support; (b) Hydraulic roof support; (c) Longwall shearer and conveyor belt; (d) Direction of mining progress along coal seam; (e) Subsidence below natural level of overlying land (shaded red). Image adapted from MSEC (2007).

The arrangement of multiple parallel longwall operations separated by pillars results in a "trough and peak" subsidence pattern across overlying grazing land (Figure 33). The length, width, and depth of this subsidence depends on the layout and volume of the removed coal panel; the geology of overlying materials, the depth of operations; and the type of landform (Lechner *et al*., 2016). The lowest points within subsidence troughs reported for the Bowen Basin are 2 metres (Lechner *et al*., 2016) and these may extend for kilometres above the underlying collapsed mining operations.

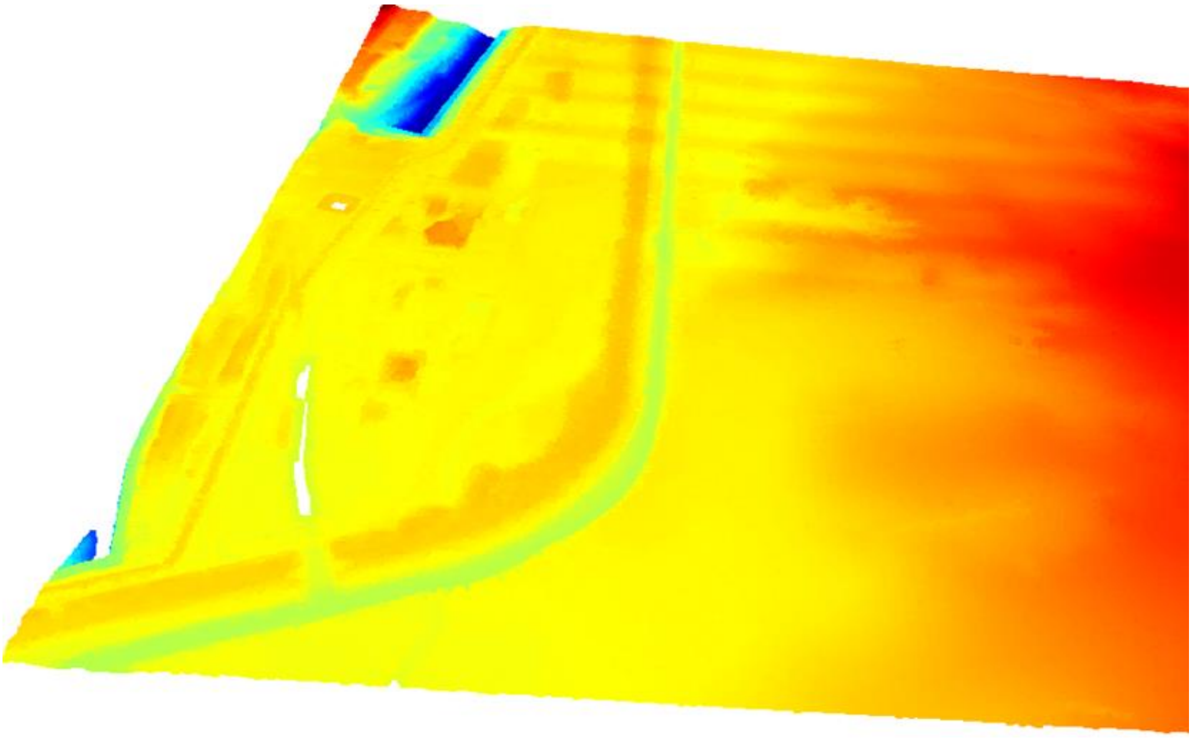

Figure 33. Lidar image illustrating a series of peak and trough surface subsidence areas (top third of the image) overlying a longwall operation in the Bowen Basin. Red represents land that is higher than yellow areas which are in turn higher than green and blue respectively.

The most significant implications longwall mining disturbed land have for livestock production relate to the effects of subsidence on (a) hydrology, (b) risk of injury to livestock and humans posted by surface cracking, and (c) tree health via the shearing of roots during land deformation.[73]

Modifications made to the overlying landforms by subsidence may modify natural waterflows both across the surface and through the soil profile. On the one hand, diverted water courses may cause pooling within subsided areas or run along troughs in a manner that causes erosion. On the other hand, ground fissures may appear along the edges of pillars, or the bulk density of overlying soil may change in a way that either increases or decreases water infiltration rates (Lechner *et al*., 2016).

Lechner *et al* (2016) notes that subsidence may have less impact on rolling downs type landscapes as these have well-developed drainage systems that prevent water diversion by the extent of peak and trough subsidence patterns. They anticipate that that this type of mining disturbance may not adversely affect pre-mining farm management activities in the Bowen Basin. Darmody *et al* (2019) propose that where subsidence does cause problems for agriculture within this region it will relate to erosion rather than drainage issues. Thus, the

[73] Longwall mining can have far more profound effects on the environment. For example, Jankowski reports that the fracturing of geological strata can expose ground water to fresh rock which may in turn cause chemistry mobilising reactions that release cations, anions, and metals from rocks into underground water systems (Jankowski, 2007). Where subsidence causes cracking of creek beds and wetlands, these changes in water chemistry may impact downstream water quality. Morrison *et al* (2019).

maintenance of groundcover on slopes associated with subsidence is of critical importance for supporting resilient post-mining land use operations.

Where significant disturbance occurs in the form of ground fissures or drainage impediments, the mining companies partnering with this project undertake remediation works such as:

A. Ploughing fissures

The ploughing of emerging ground fissures aims to prevent water from draining down these and causing erosion (Darmody, 2000). The underlying subsoil is frequently sodic and this increases the risk of erosive activity.

B. Engineered drainage structures

Where subsidence interrupts normal water courses, rehabilitation operations may install rock-lined drains or grass-covered easements to restore these.

Except for hydrological changes and potential ground cracking caused by subsidence from longwall mining, the impacted land is generally characterised by the same biophysical characteristics as undisturbed land. Mining companies may exclude grazing activities from actively subsiding areas. Once stabilised, graziers implement the same continuous grazing practices typically implemented on adjacent undisturbed areas.

8.3.1 Opportunity land disturbed by underground coal mining affords the livestock industry

Since well-planned subsidence over underground longwall mining has a relatively low impact on livestock production as a post-mining land use activity, this project assumes that managing the remediation of historical degradation by less than satisfactory grazing management remains the priority for this land type. As such, the opportunity that this kind of disturbed land affords the livestock industry is likely the same as that proposed for undisturbed mining land. Livestock producers may benefit by servicing the establishment of a silvopastoral model that increases carbon sequestration in trees, builds biodiversity, and optimises beef production from these areas. *Nevertheless, there may remain scope for designing a silvopasture that takes advantage of the hydrological changes caused by trough and peak subsidence patterns.*

8.4 Environmental Authority completion criteria listed for grazing PMLU in the Bowen Basin

Mine name	Conditions of land rehabilitated for grazing
Dawson	Land suitability Class 4; 40-60% grass cover; Biomass 1 tonne DM/ha
Callide	• Land is to be certified as suitable for beef cattle grazing land use in accordance with the Land Suitability Assessment Techniques described in Technical Guidelines for the Environmental Management of Exploration and Mining (Department of Minerals and Energy; 1995). • Adequate water infrastructure for grazing purposes. • An appropriately qualified person has predicted and defined the expected stocking rates of the rehabilitated land, and these have been agreed with relevant stakeholders. • Certification in the Rehabilitation Report that the topsoil chemical properties do not limit the suitability of the land for the intended land use and are consistent with the following: - soil salinity content is intended land use and are consistent with the following: (a) soil salinity content is <0.6 dS/m; (b) soil pH is between 5.5 and 8.5; (c) soil exchangeable sodium percentage (ESP) is <15%; (d) nutrient accumulation and recycling processes are occurring as evidenced by the presence of a litter layer, mycorrhizae and/or other microsymbionts; and (e) adequate macro and micronutrients are present.
Baralaba	• Establish a stable landform and revegetate with pasture species which may support cattle grazing and will be compatible with the surrounding “new” landform. • >70% groundcover • Slope < 5%
BHP mines: • Blackwater • Norwich Park • Wards Well • Daunia • South Walker Creek • Poitrel • Braeside	• Land suitability class ≥ 3 or not different from pre-existing class if ≥ 4 • Groundcover > 50% • 70% slopes < or equal to 20%. • Leucaena < 250 stems > 2M height/ha (1 per 40m^2) mean total area. • Retention of water infrastructure that can support livestock production as a post-mining land-use.
Minyango	• Evidence that cattle grazing can occur on rehabilitated areas, comparable with reference sites. • Groundcover is (a) established and self-sustaining and is (b) free from declared weed species; (c) comprises vegetation of similar species richness and species diversity to pre-selected analogue sites; (d) the maintenance requirements for rehabilitated land is no greater than that required for the land prior to its disturbance caused by carrying out the mining activity(ies)." • Livestock can be excluded from slopes unsuitable for grazing • > 70% groundcover, or > 50% if rocks and logs are present. • No bare surfaces > 20m^2 or longer than 10M down a slope. Evidence that composition is similar to reference sites. • Evidence in the Rehabilitation Report that soil properties (e.g. pH, salinity, nutrient content, sodium content) provide a suitable growth medium for relevant vegetation species.

	• Stock are prevented from accessing water unsuitable for their drinking requirements.
Sojitz	• Information unavailable during survey
Oaky Creek	• Native vegetation and low intensity grazing • Slopes < 25% on land rehabilitated for grazing • No evidence of vegetation dieback across the certification areas. • Species richness and vegetation cover are similar to the species richness and vegetation cover at analogue sites. • Any contaminated soils are remediated and rehabilitated
Yarrabee	• Light intensity grazing • 70% palatable grass cover. • Vegetation dominated by palatable grass and legume species. • Pest and weed density comparable to reference sites. • Growth medium has physical properties (e.g. rockiness, depth of soil, plant available water) that are adequate for supporting sustainable vegetation growth and chemical properties do not limit its suitability for growth. • Low density wooded vegetation for livestock shelter. • Ameliorate spoil to 200mm to suitably stabilise the landform and promote vegetative establishment. • Hazards in grazing land no different from hazards in analogue sites • Erosion rates comparable to reference site.
Comet	• Slopes are < 15%, though maybe < 25% on areas covered by suitable Permian spoils • Achievement of Land Suitability Class between 2 & 4. • ≥ 50% established and persistent vegetative groundcover for all slopes from 0-15%. • ≥ 80% established and persistent vegetative cover for slopes from 15% to 25%
Curragh	• Requires 30-year post mining management plan unless they can demonstrate it is completely resilient.
Jellinbah	• Established to endemic pasture species • Slopes < 20% and < 50M long
German Creek	• Land Capability Class VI • Slope < 10%
Middlemount	• Low intensity grazing (< 0.07 AEU/ha) of native pastures • Land Suitability Class 2,3,4 • Slope < 18.5% • > 70% vegetative cover. • Non-vegetative cover (rocks etc) covers less than 30%. Bare surface areas not larger than 20m^2 and five-year average bare areas cannot be longer than 10M along a slope. • Non-native cover crop grasses constitute less than 20% of total vegetative cover • Stocking rates will be revised based on field trials and establishment of reference sites during mine operation.
Clermont	• Information unavailable during survey
Grosvenor	• Subsided areas achieve Suitability Class C and Agricultural Class 3/4 suitability.

Olive Downs	• Low intensity grazing • Landform is stable when grazed during a variety of climatic conditions • Vegetation consistent with grass species suitable for grazing (e.g. including Buffel Grass (*Cenchrus ciliaris*), Wiregrass (*Aristida sp.*) and Kangaroo Grass (*Themeda triandra*) and comparable to relevant rehabilitation monitoring reference sites. • Vegetation cover and densities are comparable to relevant rehabilitation monitoring reference sites, for a period of at least five years postmining. • Weed diversity and abundance is comparable to relevant rehabilitation monitoring reference sites. • Pests do not occur in substantial numbers or visibly affect the development of pasture grass species. Cattle stocking rate monitoring demonstrates the long-term carrying capacity of a stocking rate of 0.22 adult equivalents per hectare is achievable
Peabody/Coppabella	• The pre-mining agricultural suitability class was 2 and this will become 4-5 on post-mining rehabilitated land.
Mertres	• Grazing land of Agricultural Suitability Class 2-3
Stanmore Coal	• > 70% ground cover and no bare dirt patches > 20m^2 or longer than 10M down slope. • Demonstrate areas can recover post-grazing or after fire
Hail Creek	• Evidence that at least condition B of "ABCD grazing land condition framework" has been achieved. • Evidence of spoil which demonstrates acid rock drainage (ARD) and/or spontaneous combustion risks have been managed appropriately • Evidence of spoil sodicity assessment and management of problem spoils with spoil remediation method. • Implementation of engineering and capping designs promoting containment of potential hazardous material or contaminated waste material. • Evidence that rehabilitated land has a rate of erosion similar or below that in the relevant reference sites. The applicable relevant reference sites must have similar chemical and physical characteristics including slope length as that of the rehabilitated area.
Newlands	• Self-sustaining vegetation for grazing • Slope < 15% • > 70% vegetation cover (at least 6 grazing species). • > 80% vegetation cover on creek diversion banks with evidence of recruitment in the last 5 years (collected during monitoring and assessment program).
Collinsville	• Self-sustaining vegetation for grazing • Slope < 15% • > 60% overall groundcover, > 6 grazing species
Peabody	• 5-20% slopes

8.5 Questionnaire for mining companies

This project seeks to describe an implementation gap for applying regenerative farming practices to rehabilitated land and historically degraded farming land owned or leased by mining companies. The following questions attempt to ascertain how mining companies manage the grazing of these land types in the Bowen Basin. It also seeks to understand how the livestock industry may partner with the coal mining industry in achieving mutually beneficial outcomes for this land through the mine closure process.

8.5.1 Grazing management of undisturbed land *that will not be mined* in the Bowen Basin

These questions relate to land that the mining company owns or manages that sits outside a mining lease area or is unlikely to be subject to a production permit.

a. What kind of arrangements does the company put in place to govern the use of undisturbed land for grazing purposes by third parties. For example:
    i. Pasture maintenance (e.g. species, groundcover %, pasture utilisation %).
    ii. Trees and shelter
    iii. Riparian zones
b. What grazing systems are used by pastoralists managing the company's undisturbed land?
    i. Unaware
    ii. Continuous grazing
    iii. Rotational grazing
    iv. Multi-camp rotational grazing
    v. Time-controlled grazing
    vi. Other
c. Does the company keep soil carbon and/or biodiversity measurements for this type of land?
d. What, if any, carbon sequestration targets (tonne/hectare $year^{-1}$) are set for this land type?
e. What biodiversity targets, if any, have been set for undisturbed land (e.g. BioCondition score)?
f. What goals does the company have for land that will likely remain undisturbed until mine closure?

8.5.2 Grazing management of rehabilitated land in the Bowen Basin

a. How does the mining company determine fencing, shelter, and water infrastructure layout for rehabilitated areas?
b. What arrangements does the company make with third party pastoralists for grazing rehabilitated areas?
c. What managemet constraints does the company put on the grazing of rehabilitated land by third parties?
    i. Minimum ground cover %

ii. Pasture DM utilisation %
iii. Invasive weed management
iv. Weather events (mm/day)

d. What carbon sequestration targets does the company set for rehabilitated land?
   i. Above ground (tonne/hectare $year^{-1}$)
   ii. Below ground (tonne/hectare $year^{-1}$)
e. What biodiversity targets does the company set for rehabilitated land (e.g. BioCondition score)?
f. Does the mining company have data on the biomass yield (tonne DM/hectare $year^{-1}$) for rehabilitated land in the Bowen Basin?

8.5.3 Biophysical context of rehabilitated land

a. What is the highest slope gradient intended for land rehabilitated for grazing purposes?
b. What shade and water infrastructure is deployed on this type of land? Negotiation
c. Maintenance requirements for engineered drainage?

8.5.4 Regenerative pastoral services

a. Does the mining company assess the monetary value of:
   i. Carbon sequestration/hectare year-1?
   If yes, please provide further explanation.

   ii. Biodiversity enrichment/BioCondition points?
   If yes, please provide further explanation.

b. How might a pastoralist benefit from providing scientifically validated carbon sequestration or biodiversity building services for your company?
   i. They would not benefit beyond lease agreements
   ii. They may claim carbon or biodiversity point credits
   iii. The company would pay a fee for implementing specific carbon and biodiversity building practices.

8.6 Visual comparisons of properties with neighbouring conventionally managed land

Two project participants provided images that compare land condition on areas treated with adaptive grazing methods with continuously grazed neighbouring properties. These images were obtained from historical publications relating to the benefits of adaptive grazing management has for maintaining groundcover and “rain readiness.” It has not been possible to determine the level of objectivity practiced in determining the location of images.

8.6.1 Property C (Baralaba)

Figure 34: Images of groundcover taken on the same day for a continuously grazed and managed property (Right) and Property C (Baralaba) that uses Time-Controlled Grazing (Left)

8.6.2 Property D (Gogango)

Figure 35: Images of groundcover taken on the same day for a continuously grazed and managed property (Left) and Property D (Gogango) that uses Time-Controlled Grazing (Right)

8.7 Recommended tree species for incorporation within a silvopasture established on sloped rehabilitated landforms

It is expected that there are many commercially relevant species that can be considered for integrating within the proposed silvopasture for establishment on sloped grazing PMLU land. This report makes four specific recommendations for further consideration.

8.7.1 Leucaena

Benefits summary:

- *Nitrogen fixing (Legume)*
- *Can achieve significant reductions in methane emissions*
- *High-yielding highly-quality forage*

The potential the introduced legume Leucaena has for increasing the profitability of livestock production on marginal land in Northern Australia is well-documented (MLA 2021). The plant yields forage of extremely high nutritional value: 20-25% Crude Protein (CP) and a digestibility of > 60%. Research has demonstrated that supplementation of a Rhodes grass diet with up to 44% Leucaena may decrease methane emissions by up to 15% per unit digested OM intake (Kennedy and Charmley 2012). Assuming an RUE of 4.0 (MLA 2021), Leucaena has the potential to produce 2-2.4 tonnes of available DM/ha year^{-1} in the Bowen Basin depending on soil nutrient conditions. These observations indicate that the use of Leucaena within a silvopastoral approach to managing rehabilitated land provides an opportunity support profitable livestock production.

Leucaena is already planted in hedgerows on degraded agricultural land to improve soil structure and hydrology:

> Leucaena planted across the slope (along contours) with vigorous grass cover between rows encourages water infiltration, decreases run-off and so reduces sediment load in local waterways. In central Queensland, established Leucaena pastures have reduced run-off, soil loss and sedimentation after high intensity rainfall.[74]

The approach suggested here aligns with the silvopastoral model presently recommended for implementation on rehabilitated spoil landforms. Admittedly, Leucaena is most productive on deep, fertile, and well-drained soils. It can, however, grow on dry saline soils if one accepts an extended period of establishment (MLA 2021).

A reluctance to use Leucaena in open cut coal mine rehabilitation

Understandably, some mining company project partners express reservations about intentionally establishing Leucaena within rehabilitated areas on account of its introduced status and potentially invasive nature. Where it has already become established, the EA criteria for rehabilitation for at least one mining company sets a maintenance requirement of a maximum Leucaena density of < 250 stems/hectare (1 per 40m^2) of > 2 metre height over the mean total rehabilitation area.

[74] M. Shelton, S. Dalzell, N. Tompkins, S. Buck, *Leucaena: the productive and sustainable forage legume* (MLA 2021), p. 64.

The silvopastoral approach recommended here seeks to mitigate the risk of Leucaena becoming a weed:

C. The silvopastoral approach's operation of rehabilitated areas as a managed ecosystem can incorporate The Leucaena Code of Practice (See The Leucaena Network).
D. The objective of increased productivity from rehabilitated areas motivates the optimisation of Leucaena biomass and this prevents the overgrowth of plants.
E. The use of emerging less invasive commercial varieties.[75]
F. The parcellated nature of rehabilitated areas provides a natural border area for Leucaena management within the silvopasture.

Limitations of recommendation

The most obvious limitation of Leucaena within the proposed approach is its potential for earlier varieties to become an invasive weed if poorly managed. To some extent the problems some mining companies have experienced within Leucaena may have emerged from the leasing of land to graziers that have not observed best practice grazing principles. The digitally enabled approach recommended within this report would allow mining companies to guide the management of Leucaena by third parties.

8.7.2 Acacia victoriae

Benefits summary:

- *Nitrogen fixing (Legume)*
- *Revenue diversifying (Wattle seed production for human consumption)*
- *Drought resilient forage production*

The ability of many leguminous Acacia species to fix nitrogen in the soil, withstand relatively dry conditions, and establish quickly lead to their regular use in the revegetation of rehabilitated land in the Bowen Basin. This project makes a specific recommendation for incorporating *A. victoriae* (Figure 36) within the proposed silvopastoral approach for the following commercial reasons.[76]

First, the tree is the main species used for wattle seed production in Australia.[77] Though the literature suggests that trees can produce as much as 1.2 tonne raw wattle seed/hectare year^{-1} (Simpson and Chudleigh, 2001), a more realistic figure that accounts for losses within the harvesting and threshing process is 300kg net (A. Jones, Wattle-We-Eat Pty Ltd, Pers. Comm). The current market price of raw seed from *A. victoriae* is

[75] Extant areas of Leucaena invasion are generally attributed to an earlier "woody Leucaena" first introduced in the late 1800s. MLA 2021. Progress is being made on the breeding of sterile Leucaena varieties (Nigel Tompkins, Pers. Comm.).

[76] Note that a survey of mining company species selection for revegetating rehabilitated areas revealed the use of *A. victoriae* on only one mine site in the Bowen Basin.

[77] For background on the development of a wattle seed industry in Australia see S. Simpson, P. Chudleigh, *Wattle Seed Production in Low Rainfall Areas* (A report for the RIRDC/Land & Water Australia/FWPRDC Joint Venture Agroforestry Program, 2001); G. Olsen, "Broadscale production of wattle seed to address salinity: potential and constraints," *Conservation Science W.A.* 4 (2002) 185-191; K. Bryceson, *Value chain analysis of bush tomato and wattle seed products* (DKCRC Research Report 40. Desert Knowledge Cooperative Research Centre: Alice Springs, 2008).

$80/kg. If a more conservative price of $50/kg is assumed, the harvesting of *A. victoriae* could return as much as $15,000/ha year^{-1}. This yield calculation is derived from a case study that observed this production from 600 trees/hectare receiving 400mm rainfall/year (A. Jones, Wattle-We-Eat Pty Ltd, Pers. Comm). Therefore, it seems possible that production could be marginally higher within the Bowen Basin where rainfall exceeds 500 mm/year. The recommendation that mining companies consider incorporating *A. victoriae* within a silvopasture for rehabilitated land anticipates that a small wattle seed production industry could emerge as a post mining land use that integrates with livestock production. This approach to recommericalising rehabilitated landforms has potential for developed partnerships with local indigenous communities.

The second commercial reason for considering the incorporation of *A. victoriae* in the proposed silvopastoral approach relates to its potential value as a back-up forage crop during drought periods. A significant amount of research was undertaken on the use of *A. victoriae* within a silvopasture in arid regions of Israel (Mor-Mussery *et al*., 2013; Helman *et al*., 2016). Mor-Mussery *et al* (2013) concluded that *A. victoriae* had great potential for rehabilitating degraded dryland, providing palatable forage for livestock production, and sequestering significant quantities of above and below ground carbon.

In a separate Israeli study, Helman *et al* (2016) compared the suitability of *A. victoriae* and *A. saligna* for use within a silvopasture. They found that *A. victoriae* produced forage of a higher nutritive quality than *A. saligna*. Furthermore, though both shrubs had similar canopy architecture, they reported that a smaller litter fall from *A. victoriae* resulted in higher biomass yields from non-legume understory plants in this silvopasture compared with that observed in *A. saligna* silvopastures.[78]

It seems likely that *A. victoriae* would meet the threshold of regrowing > 1 tonne of available biomass DM/hectare year^{-1} regarded as the lower commercially viable limit for forage trees (LeFroy 2002). In a study that modelled annual biomass availability for sheep and goats in a region with very low annual rainfall (232mm), Mor-Mussery *et al* (2013) reported that 250 *A. victoriae* trees/hectare produced a renewable 880kg DM/ha year^{-1}. Since they modelled the available biomass available to goats as being less than 2 metres, it seems reasonable to assume that the annual regrowth availability for browsing by larger cattle under the relatively wetter conditions of the Bowen Basin (i.e. > 520mm versus 232mm) would be above 1 tonne/hectare.[79]

Unfortunately, there is no published data to determine if the digestibility of *A. victoriae* foliage or its seed pods is greater than the minimal requirement of > 55% for maintaining liveweight (LeFroy 2002). Mor-Mussery *et al* (2013) and Helman *et al* (2016) comment on its palatability for livestock and McMeniman *et al* (1989) report that its foliage contains almost 15% CP which is higher than the minimal nutritional requirement for grazing beef cattle (MLA, 2015). Further investigations, however, are

[78] Note that a survey of species used by the partnering mining companies revealed that *A. saligna* is commonly included within seed mixes. The survey revealed that *A. victoriae* was included in seed mixes at just one mine site.

[79] Further work on the use of *A. victoriae* in Israel has halted because the species has been subsequently designated an invasive weed in that country. See J.M. Dufour-Dror (2016).

required to confirm the digestibility of foliage and seed pods. At a minimum, it seems that in addition to providing diversified revenue from wattle seed production, *A. victoriae* has the potential to provide fodder during prolonged dry periods.

There are additional benefits for incorporating this Acacia species within the proposed silvopasture:

A. The additional revenue created from supplying the growing wattle seed market alleviates pressure on resources for livestock production.
B. *A. victoriae* is moderately salt tolerant (Joseph *et al*., 2015)
C. Wattle seed can be stored for up to 10 years and this helps to overcome any short-term inconsistencies in demand within an expanding market.
D. As a native to inland arid areas of Australia, this plant requires no irrigation for establishment or maintenance.
E. The water requirements required to support *A. victoriae's* flowering and seed filling in October-November align with Bowen Basin's rainfall pattern.
F. Pruning and harvesting operations create post-mining land use employment opportunities. For example, the cost of harvesting by hand is approximately $600/hectare and the trees may require pruning at a cost of $280/hectare over the first three years to ensure development of good form (A. Jones, Wattle-We-Eat Pty Ltd, Pers. Comm.).
G. Trees are typically hand-harvested (two people can harvest one hectare of trees/day) is also attractive considering that mining operations seek to minimise traffic on rehabilitated areas.
H. Trees may grow for more than 20 years (A. Jones, Wattle-We-Eat Pty Ltd, Pers. Comm.).

Figure 36. *Acacia victoriae* (Source: Australian Plant Image Index. dig.44204)

Limitations of recommendation:

Wattle seed production remains a relatively new and expanding market. The nearby Woorabinda Aboriginal Shire Council has recently engaged in the development of a wattle seed production project.

There are no peer-reviewed investigations of silvopastures containing A. victoriae in Australia. It would be relatively simple to obtain samples from foliage and seed pods from trees already growing on rehabilitated areas in the Bowen Basin for digestibility analysis. Small trials, however, need to be undertaken to confirm biomass production potential and to determine ideal spacing of plantings and canopy architecture to optimise the growth of interrow ground cover.

8.7.3 Pongamia (*Pongamia pinnata*)

Benefits summary:

- *Nitrogen fixing (Legume)*

- *Oil producing*
- *High carbon sequestering and soil building*

Though the leguminous native Pongamia's foliage and seed pods are unpalatable for livestock, the integration of Pongamia within a silvopasture established on rehabilitated land within the Bowen Basin offers the following benefits:

A. It is a leguminous tree with a significant capacity to sequester carbon. Under optimal conditions it is reported to sequester above and below ground carbon of up to 30 tonne/hectare year^{-1} (Mitra *et al*., 2021). In addition to stabilising slopes and improving soil OM, its incorporation within a silvopasture has the potential to support carbon-neutral livestock production by offsetting carbon emissions.
B. It produces large oil-rich seeds (40-50% by volume) and oil yields of 1000-5000L/hectare year^{-1} depending on the biophysical context. This compares with soybean (0.8 tonne/ha year^{-1}), canola (1.5 tonne/ha year^{-1}) and palm oil (5 tonne/ha year^{-1}). Unlike these crops, however, Pongamia can grow on marginal land and avoid competing for land used for food production. The trees remain productive for more than 35 years. Though there is not yet an established biofuel industry within Australia that uses Pongomia oil as a feedstock, this is occurring in other countries (Scott *et al*. 2008). Establishing a plantation now would build a regional oil bank for the future and diversify revenue generated from land rehabilitated for grazing purposes.
C. It grows a dense network of lateral roots that reduce erosion, and it is deep rooting, drawing on water from 10 metres underground (P. Gresshoff, Pers. Comm.).
D. The canopy's architecture is conducive to dropping high N containing pods on interrow pasture spaces, increasing nutrient recycling and soil development.
E. Livestock can graze interrow pastures after three years of tree establishment.

From a social perspective, the successful incorporation of Pongamia within a silvopastoral approach to rehabilitating land in the Bowen Basin provides the potential for generating future economic activity from biofuel production. Furthermore, such an industry would derive feedstock for biofuel production from land not used to produce important food crops and provides a carbon-offset for the local livestock production industry.

Suitability for establishment on rehabilitated land in the Bowen Basin

Pongamia is a leguminous tree native to Northern Australia and Southern/South Eastern Asia. It has adapted to growing in sodic soils containing high levels of salt (i.e. up to an EC of 20 dS/m^2) and can grow with low water and nutrient availability (Gresshoff *et al*., 2017).[80] The tree can grow on sandy and clay soils with as little as 500mm annual rainfall, withstand long periods without rain (up to 4 months), and can survive temperatures in temperatures exceeding 45˚C. Its seedlings are capable of withstanding extensive periods of water deprivation (25 days to 55% relative water content) without significantly affecting growth and biomass production.

[80] Gresshoff *et al* (2017) indicate that the germination rate of Pongamia seed is higher when water is slightly saline.

Trees have already been successfully established in spoil materials on rehabilitated coal mining land at Meandu, Queensland with > 95% seedling survival (Figure 37; Gresshoff *et al*., 2017). After five years of establishment, University of Queensland researchers have observed that ground cover under Pongamia trees is significantly greater than that observed under Acacia and Eucalypt species grown on the same slopes (P. Gresshoff, Pers. Comm).

Figure 37. A Pongamia pinnata tree established in spoil with minimal drip irrigation on rehabilitated land near Meandu, Queensland (Photo used with permission from P. Gresshoff).

The planting and establishment of trees on rehabilitated slopes at Meandu proceeded as follows (P. Gresshoff. Pers. Comm.):

A. Slopes were covered in topsoil to a depth of 300mm.
B. Seed pods were planted on the upslope side of a contour bank to increase water availability.
C. Seedlings received minimal irrigation for the first two years.

Limitations of recommendation:

The successful establishment of Pongamia on rehabilitated slopes at Meandu suggest that Pongamia may be suitable for establishing within a silvopasture on rehabilitated spoil landforms in the Bowen Basin. Due to the relatively lower rainfall within the Bowen Basin (520-600mm versus 780mm at Meandu), the establishment process will require a higher reliance on drip irrigation during the first two years. Moreover, it seems that

Pongamia may require topsoil to a depth of 300mm, though it remains to be seen if a generous application of municipal council waste can make this unnecessary.

After five years the trees are now 2-3 metres tall and no longer require irrigation. The investment in drip irrigating the trees for the first two years may be cost-effective considering that the trees will remain productive beyond 35 years and live longer than 100 years.

8.7.4 Leptospermum polygalifolium

Benefits summary:
- *Revenue diversifying via Manuka honey production*
- *Introduces productivity into rehabilitated areas that exclude grazing (e.g. rock armoured slopes; areas adjacent to voids)*
- *Native species*
- *Public interest*

Leptospermum polygalifolium is a native shrub found along the east coast of Queensland. It is one of several Leptospermum species that produce nectar from which bees make valuable bioactive Manuka honey.[81] Manuka honey contains a chemical compound (methylglyoxl; MGO) that is derived from a called dihydroxyacetone (DHA) in the nectar from these species (Owens *et al*., 2019). MGO is an antimicrobial agent that is effective against a wide range of pathogens, including drug resistant bacteria (Adams *et al*., 2009).

This report recommends the consideration of *trialling* its establishment in monocultural plantations on rehabilitated areas, especially rock armoured slopes and hill tops, to service the Manuka honey market as a post-mining land use. This recommendation departs from the previously recommended tree species in two ways. First, it is not a legume and will, therefore, have a smaller capacity to build topsoils. In fact, as for Pongamia, it seems likely that *L. polygalifolium* will need to be planted into topsoil (discussed further below). Second, the species is unpalatable to livestock but also at risk of trampling by livestock. As such, its establishment within a silvopasture will require either (a) the use of virtual fencing to keep livestock from walking through bush lined contours or (b) its confinement to dedicated *L. polygalifolium* plantation areas from which cattle are always excluded.

Virtually no peer-reviewed research exists on the establishment of commercial plantations (e.g. soil nutrient and moisture requirements). Nevertheless, University of the Sunshine Coast researchers have observed *L. polygalifolium* occurring naturally on ridges west of Rockhampton and within 150km of open cut coal mines in the Bowen Basin (S. Williams, Pers. Comm.). The recommendation in this report is for mining companies to trial this species on rehabilitated areas. The benefits of the successful establishment of a *L. polygalifolium* plantation for rehabilitated land in this region are the following:

[81] It is one of several Leptospermum

A. It enables monofloral Manuka honey production which increases the product value by avoiding dilution of antimicrobial compounds with non-Leptospermum nectar. This would make these plantations more commercially attractive for beekeepers than relying on the production of (potentially diluted) multifloral Manuka honey from naturally occurring Leptospermum shrubs in mixed species forests.
B. Realistically, a Leptospermum plantation could support one hive/hectare, and this can produce 40-50kg honey over the species' 2-month flowering period. Mono-floral Manuka honey currently sells for $53/kg, though it has previously sold for as much as $250/kg. On current prices, a plantation could earn between $2,120-$2,650/ha $year^{-1}$ 18 months after planting (T. Allender, Pers. Comm).
C. European bees are limited to accessing nectar within a four-kilometre radius of their hive. Where a buffer zone of 4km can be achieved between a Leptospermum plantation and public access, exclusive access to plantations can be contractually agreed with honey producers. Moreover, since beehives can be located kilometres from the nectar source, this industry does not require on-the-ground access to trees and this may allow for accelerated pre-mine closure commercial activity on rehabilitated land.
D. *L. polygalifolim* can become productive 18 months after planting.
E. Attracts positive public interest by supporting the strengthening of an apiary industry within Central Queensland, which in turn supports the agricultural industry on account of the crucial role bees play in food security through the pollination services they provide.

Limitations of recommendation

As already mentioned, there are no peer-reviewed studies to inform the establishment of Leptospermum plantations within Central Queensland. Though L. polygalifolium has been observed growing naturally within 150km of Bowen Basin mine sites (S. Williams, Pers. Comm.), the latter receives approximately 150mm less annual rainfall. It seems likely, therefore, that a plantation will require minimal drip irrigation during initial shrub establishment and during a two-month nectar flow in late spring, early summer.

It remains to be seen if Leptospermum establish directly into spoil amended with OM. At the very least, it seems that the plant will need to be planted on the upslope side of contoured mounds to increase water availability. It may be possible to create a box line of topsoil along the contours to support the plant growth and survival, thought this may increase competition from weed species. Since a plantation may create a revenue stream of above $2,000/hectare $year^{-1}$, it may be economically feasible to employ workers to maintain a weed free ground cover around shrubs.