THE DEVELOPMENT OF DRAFT COMPLETION CRITERIA FOR UNGRAZED REHABILITATION PASTURES AFTER OPEN-CUT COAL MINING IN CENTRAL QUEENSLAND

FINAL REPORT ACARP Project C8038

THE UNIVERSITY OF QUEENSLAND

ACARP
Australian Coal Association Research Program

CENTRE FOR MINED LAND REHABILITATION

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EXECUTIVE SUMMARY

There currently exist no formal criteria on which to assess the success of rehabilitated areas following open-cut coal mining in central Queensland. Guidance is provided in the *Technical Guidelines for Environmental Management of Exploration and Mining in Queensland* (DME 1995), however there is some urgency in developing completion criteria that are practical, defensible and are appropriate for the local conditions experienced. As an initial step in developing completion criteria, it is important to understand the main factors influencing the successful creation of a stable landform, its associated vegetation cover and long-term persistence. Silcock (1991) reviewed rehabilitation efforts on central Queensland coal mines in 1990, and recommended that long-term monitoring programs be established, along with further research, to refine rehabilitation techniques and improve confidence that the approaches taken were leading to the creation of stable and sustainable landscapes. Since then, a considerable body of information has been accumulated on erosion processes and landform design, and vegetation persistence and performance over time, to assist in this direction.

Within this context, funding was sought from the Australian Coal Association Research Program (ACARP) to review specifically pasture-based rehabilitation efforts in central Queensland, and to make progress towards the development of completion criteria suitable for relinquishment purposes. Pasture-based rehabilitation constitutes approximately half of all rehabilitation efforts in central Queensland, with historical links to improved pasture recommendations for the region and in some cases to lease conditions designating a return to grazing purposes. Rehabilitation pastures covered an estimated 8000 ha in 1997 and on present trends may cover an additional 15,000 ha of land presently disturbed by mining. At the time of this study, these systems had not been subjected to grazing, and the draft criteria developed address these systems in their unmanaged state. The impacts of grazing are currently being specifically addressed in a separate ACARP Project C9038 "*Sustainable grazing on rehabilitated lands in the Bowen Basin*".

The majority of this document details collated data and analyses from the review of available information (Component 1). Embedded within the report are a set of draft completion criteria derived from the review, with input from individuals experienced in rehabilitation issues in the region (Component 2). These criteria are considered to capture the main factors driving successful pasture-based rehabilitation. However, supporting data are in some cases limited and further monitoring and research are required to gain greater confidence in their application. The study of fire effects on pasture recovery (Component 3) is included as an appendix, with relevant outcomes integrated into the appropriate sections of the review.

Draft criteria are summarised below and cover fundamental parameters for surface stability and vegetation performance. More detailed discussion of the criteria can be found in Chapter 2:

1. Achieve and maintain vegetation cover of at least 70%. Vegetation cover forms the single most important control on erosion. Erosion rates are significantly reduced for cover levels of 50% but higher cover levels are considered necessary for adequate control. Soil movement can still occur at high cover dependent on other factors, below.

2. Regrade slopes to less than 12%. High levels of cover are in themselves not necessarily adequate. Significant movement can still occur for cover > 70% on slopes exceeding 12-15%. Maintaining slope gradients at less than 12% appears to be associated with low erosion rates.

3. Media properties reducing infiltration affect the influence of vegetation and slope. Surface materials which have poor particle size distribution (similar proportions of fine sand, silt and non-active or only slightly active clays) combined with elevated ESP or R1 dispersion index tend to have lower infiltration and transmission rates. Levels of runoff are higher than on rehabilitated areas with relatively favourable characteristics and erosion rates are higher through an increased volume of runoff and through dispersion. This is further compounded by lowered plant growth (as less water is available for growth). Rock content is considered to reduce erosion through surface protection in a manner similar to vegetation, and in disruption of rill development.

4. Reduce rootzone salinities to less than 0.6 dS/m (on 1:5 basis). Salinity levels of less than 0.6 dS/m in the surface 40cm support pastures with dry matter levels capable of providing the minimum cover necessary for erosion control. However, the impacts of dry matter removal through grazing may warrant a lower 'threshold' value. Low initial site salinity will assist in rapid vegetation establishment, thereby reducing the risk of erosion.

5. Media properties influence salinity reduction over time. The same factors which affect infiltration, runoff (and subsequent erosion) also impact on rootzone salinity through the development of leaching profiles. Surface materials which have poor particle size distribution combined with elevated ESP or R1 dispersion index tend to have lower infiltration and transmission rates. Slope and surface roughness (ripping) have an effect on infiltration in the short term but in the longer term their effects are minimised.

6. A minimum CEC of 8-10 is required for adequate nutrient retention. Soil fertility (available P, N and S, plus cations (mainly K)) impacts on pasture dry matter. However, past fertiliser application and spoil mixing mask longer term equilibrium levels of these nutrients. CEC provides a more usable indicator of long term nutrient status. Low CEC is mainly associated with materials containing a high proportion of coarse particles, subject to higher leaching and nutrient rundown. As a guide, materials with a sand content of 75% or more are likely to have inadequate nutrient retention capacity. Clay mineralogy will be important in determining CEC.

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1.0 INTRODUCTION

1.1 Background

It is widely recognised within the mining industry that criteria by which to assess the success or otherwise of rehabilitation efforts are required, in order to permit lease surrender and discharge the liability for mined areas. Narrow sets of indices are generally accepted as inadequate for this purpose (Doll and Wollenhaupt 1985, Elliott *et al.* 1996) and a combination of attributes at both the landscape level and addressing specific ecosystem properties appears to be required (Bellairs 1999, Ward 1999). While the properties to be assessed will be determined by the proposed end-use of the rehabilitated area, it is important to note that surface stability, and the associated quality of runoff waters, are viewed as a fundamental issues in all cases.

There currently exist no formal criteria on which to assess the success of rehabilitated areas following open-cut coal mining in central Queensland. Guidance is provided in the *Technical Guidelines for Environmental Management of Exploration and Mining in Queensland* (DME 1995), and earlier reports (e.g Leggate *et al.* 1990). However, mine closure planning is increasingly an issue in the region as a number of older operations approach end of mine life, and there is some urgency in developing completion criteria that are practical, defensible and are appropriate for the local conditions experienced.

As an initial step in developing completion criteria, it is important to understand the main factors influencing the successful creation of a stable landform, its associated vegetation cover and long-term persistence. Silcock (1991) reviewed rehabilitation efforts on central Queensland coal mines in 1990, and recommended that long-term monitoring programs be established, along with further research, to refine rehabilitation techniques and improve confidence that the approaches taken were leading to the creation of stable and sustainable landscapes. Since then, a considerable body of information has been accumulated on erosion processes and landform design, and vegetation persistence and performance over time, to assist in this direction.

Within this context, funding was sought from the Australian Coal Association Research Program (ACARP) to investigate specifically pasture-based rehabilitation efforts in central Queensland, and to make progress towards the development of completion criteria suitable for relinquishment purposes. Funding was granted under ACARP Project C8038 "*Completion criteria for pasture-based rehabilitation in the Bowen Basin*" comprising three main components; a review of current information relating to the performance of pasture-based rehabilitation, a draft set of ecologically-based completion criteria for further discussion arising from these findings, and a component addressing issues of likely disturbance and associated long-term resilience in the post-mining landscape. The latter was restricted to investigating the impacts of fire. The impacts of grazing are currently being specifically addressed in a separate ACARP Project C9038 "*Sustainable grazing on rehabilitated lands in the Bowen Basin*".

The majority of this document details collated data and analyses from the review of available information (Component 1). Embedded within the report are a set of draft completion criteria derived from the review, with input from individuals experienced in rehabilitation issues in the region (Component 2). These criteria are considered to capture the main factors driving successful pasture-based rehabilitation. However, supporting data are in some cases limited and further monitoring and research are required to gain greater confidence in their application. The study of fire effects on pasture recovery (Component 3) is included as an appendix, with relevant outcomes integrated into the appropriate sections of the review.

1.2 Scope of Review

The main aims of the Review component of the Project were to;

1. Identify factors critical in the establishment and development of pasture-based rehabilitation after open-cut coal mining in central Queensland,
2. Assess the performance of pasture-based rehabilitation in its existing unmanaged state, with particular reference to surface stability, and
3. Provide background information relevant to the drafting of preliminary ecologically-based completion criteria for pasture-based rehabilitation in central Queensland.

The Review is limited to assessing specifically pasture-based rehabilitation in the coalfields of central Queensland, encompassing operations in the Bowen and Callide Basins. These systems form a significant proportion of rehabilitation efforts, reflecting historical post-mining land-use decisions and now well-established techniques. They are characterised by a predominance of introduced pasture grasses and legume species, which may or may not also contain an open shrub or tree component. Communities dominated by native trees and shrubs, and lacking a ground layer suitable for grazing cattle, are not considered here. In addition, the Review is restricted to considering ‘conventional’ landforms where regrading to a maximum slope of 25% has occurred. ‘Ponded’ landforms are not included, although some information has been drawn from a limited set of sites where these have assisted in understanding underlying processes.

The end-use for these systems is mostly nominated for uses associated with grazing. However, there is little active management applied after establishment, and the Project focuses on these lands in an essentially unmanaged state. An assessment of the impacts of grazing on rehabilitated pastures is addressed in a separate study under ACARP C9038.

Efforts were made to include relevant information from unpublished sources, such as internal company reports, in addition to published literature where possible. However, it is recognised that the information collated will not be exhaustive.

1.3 Approach and collated datasets

The Review draws upon published articles and research papers available in the literature, published reports and unpublished internal company reports and other material where these were available. Emphasis was placed on studies originating from coal mines in central Queensland, but including information from other parts of Australia where relevant.

The Review collated information principally from rehabilitation monitoring sites but also relevant field research trials, from as many minesites in the region as possible. Minesites from which information was drawn are listed below;

- Callide
- Moura
- Blackwater
- Gregory
- Norwich Park
- Peak Downs
- Saraji
- Goonyella Riverside
- South Walker Creek
- Collinsville

Data obtained were compiled to generate a quantitative database for further analysis and interpretation. The dataset of around 500 records, which forms the core of the Review, covered approximately 130 sites or trial areas across nine mines (Callide not included in dataset) and encompassed sites of varying age, slope gradient, growth media type and associated vegetation parameters. Only those data which had been collected and reported in a similar manner were included. There was also variation in the parameters measured at each site, such that datasets became limited for some variables. During the course of data collection, it was apparent that a great deal of the historical information relating to revegetated areas for many coal mine operations in central Queensland had been lost or discarded. There is a need for a consistent approach to the collection of monitoring data and a suitable mechanism for its retention for future potential assessment.

2.0 DRAFT COMPLETION CRITERIA AND RECOMMENDATIONS

The following set of criteria have been developed from data interrogation coupled with supporting field observation and experience from a number of individuals with considerable knowledge of rehabilitation performance and issues. Criteria are limited to technical or ecological issues, and no attempt has been made to integrate social or stakeholder considerations necessary in a mine closure process. Criteria and their thresholds where stated *do not allow for the effects of introducing cattle* into these systems. These will be considered under ACARP C9038. Supporting data are in some cases limited and further monitoring and research are required to gain greater confidence in their application.

A. SURFACE STABILITY

Principle:

Surface stability is the major criterion for acceptability, forming the basis for a sustainable system and potential post-mining land-use, controlling off-site impacts and the longevity of any engineered structures. There is a high degree of overlap in the factors affecting surface stability that also affect vegetation performance. Vegetative performance itself affects surface stability.

A1. Achieve and maintain vegetation cover of at least 70% – Sections 3.5, 4.3.
Vegetation cover (standing material and fallen litter) forms the single most important control on erosion. Erosion rates are significantly reduced for cover levels of 50% but higher cover levels are considered necessary for adequate control. Soil movement can still occur at high cover dependent on other factors, below. Vegetation cover in these systems is related in a curvilinear fashion with dry matter (Figure 6, p.15). For dry matter levels affording 50% cover, small fluctuations in dry matter due to seasonal variability may cause relatively large changes in cover, constituting greater risk.

Up to two years may be required for an adequate cover to redevelop after fire.

A2. Regrade slopes to less than 12% - Section 4.4.
High levels of cover are in themselves not necessarily adequate. Significant movement can still occur for cover > 70% on slopes exceeding 12-15%. Maintaining slope gradients at less than 12% appears to be associated with low erosion rates. The influence of slope length appears dependent on the level of vegetation cover and is confounded by factors such as surface roughness.

A3. Media properties reducing infiltration affect the influence of vegetation and slope – Section 4.4.
Surface materials which have poor particle size distribution (similar proportions of fine sand, silt and non-active or only slightly active clays) combined with elevated ESP or R1 dispersion index tend to have lower infiltration and transmission rates. Under natural rainfall (generally storm) conditions, levels of runoff are higher than on rehabilitated areas with relatively favourable characteristics and erosion rates are higher through increased volume of runoff and through dispersion. This is further compounded by lowered plant growth (as less water is available for growth).

Rock content is considered to reduce erosion through surface protection in a manner similar to vegetation, and in disruption of rill development.

B. PASTURE DRY MATTER PERFORMANCE

Principle:

A suitable level of dry matter or pasture cover is required for surface stability; excess growth may under suitable management be available to support cattle grazing.

B1. Reduce rootzone salinities to less than 0.6 dS/m (on 1:5 basis) – Section 5.2.3.
Salinity levels of less than 0.6 dS/m in the surface 40cm support pastures with dry matter levels capable of providing the minimum cover necessary for erosion control. The impacts of dry matter removal through grazing may warrant a lower 'threshold' value. Low initial site salinity will assist in rapid vegetation establishment, thereby reducing the risk of erosion.

B2. Media properties influence salinity reduction over time – Section 5.2.3.1.
The same factors which affect infiltration, runoff (and subsequent erosion) also impact on rootzone salinity through the development of leaching profiles. Surface materials which have poor particle size distribution (similar proportions of fine sand, silt and non-active or only slightly active clays) combined with elevated ESP or R1 dispersion index tend to have lower infiltration and transmission rates.

Surface roughness (ripping and ridge/furrow relief) has an effect on infiltration in the short term but in the longer term its effects is minimised.

For reconstructed profiles that are initially saline, changes in salinity over time act as a tracer for water penetration. The development of a leaching profile associated with satisfactory infiltration results in a greater availability of water for plant use. Successful vegetation establishment also aids infiltration, providing a positive feedback.

B3. A minimum CEC of 8-10 is required for adequate nutrient retention.
Soil fertility (available P, N and S, plus cations (mainly K)) impacts on pasture dry matter. However, past fertiliser application and spoil mixing mask longer term equilibrium levels of these nutrients. CEC provides a more usable indicator of long term nutrient status.

Low CEC is mainly associated with materials containing a high proportion of coarse particles, subject to higher leaching and nutrient rundown. As a guide, materials with a sand content of 75% or more are likely to have inadequate nutrient retention capacity. Clay mineralogy will be important in determining CEC.

Adequate nutrition is required for production of cover, but also will assist in recovery of cover following fire or grazing, i.e. system resilience. An adequate legume component (capable of withstanding grazing pressure, if necessary) will be important in maintaining nutrition even where CEC targets are met.

3.0 CHARACTERISTICS OF REHABILITATION PASTURES

3.1 Location of the Bowen Basin coalfields

The Bowen Basin is an extensive coal-bearing formation supporting approximately 23 open-cut and underground mining operations. This coal measure extends approximately 550km from Collinsville in the north (20^{o} 30' S) to Theodore in the south (25^{o} 20' S), and is up to 100km wide (Figure 1). Two smaller outlying coal basins (Blair Athol to the west and Callide in the south-east corner) also support mining operations and are considered as part of this review.

3.2 Extent and distribution of rehabilitated pastures

Large-scale open-cut coal mining commenced at Moura mine in 1961 and at Blackwater mine in 1966. Initial pasture rehabilitation studies were commenced at Blackwater mine in 1971-72, and at Peak Downs and Goonyella mines in 1972-73 (Coaldrake and Russell 1978). All three mines have records for rehabilitated pasture areas established by 1975-76.

A survey in 1997 estimated a total area disturbed by open-cut coal mining in central Queensland at 55,500 ha (A. Armstrong, personal communication – ACMER Workshop Rehabilitation issues for the coal industry in Queensland, July 1999). Approximately 12,500 ha had been, or was in the process of undergoing rehabilitation. A further 'backlog' of 4000 ha also existed. No clear data are available, but approximately half of this area is considered to have sown pasture as the dominant vegetation type.

Pasture-based rehabilitation areas of significant size have been reconstructed on at least 11 open-cut operations in central Queensland. These are principally sites covered by the Central Queensland Coal Associates Agreement Act (1968) under which a grazing-related land-use was specified (Goonyella, Peak Downs, Saraji and Norwich Park mines). Similar approaches to rehabilitation were also applied to other operations managed by BHP Coal Pty Ltd (Moura, Blackwater, Gregory and Riverside mines) and other sites including Curragh and South Walker Creek.

Due to the nature of the open-cut mining methods, pasture areas on all of these sites are disjunct in their distribution. Typically, continuous areas of rehabilitation up to 250 ha in size, but usually smaller, are confined to inter-ramp areas bounded by two ramps and the pit low wall. Access is via the regraded box-cut slope.

3.3 Seed mixes and rates

Documentation of historical seed mixes is poor, but seeding of pastures is likely to have followed recommendations arising from early trial work in the region. Roe *et al.* (1996) and Kelly (1979) indicate that initial seed mixes were predominantly *Cenchrus ciliaris* and *Chloris gayana* at rates of 5kg/ha and 3kg/ha, respectively, together with the legume *Macroptilium atropurpureum* at 2kg/ha. These three species dominate sites rehabilitated in the 1970's and early 1980's, lending support to such seed mixes. On rehabilitated areas established during the 1980's, the presence of *Panicum maximum* var. *trichoglume* (Green panic) and a shrubby legume *Stylosanthes humilis* suggest these were also commonly present in the seed mix. These species were known to have been included in trial work through the late 1970's and early 1980's (e.g Russel 1974, 1975).

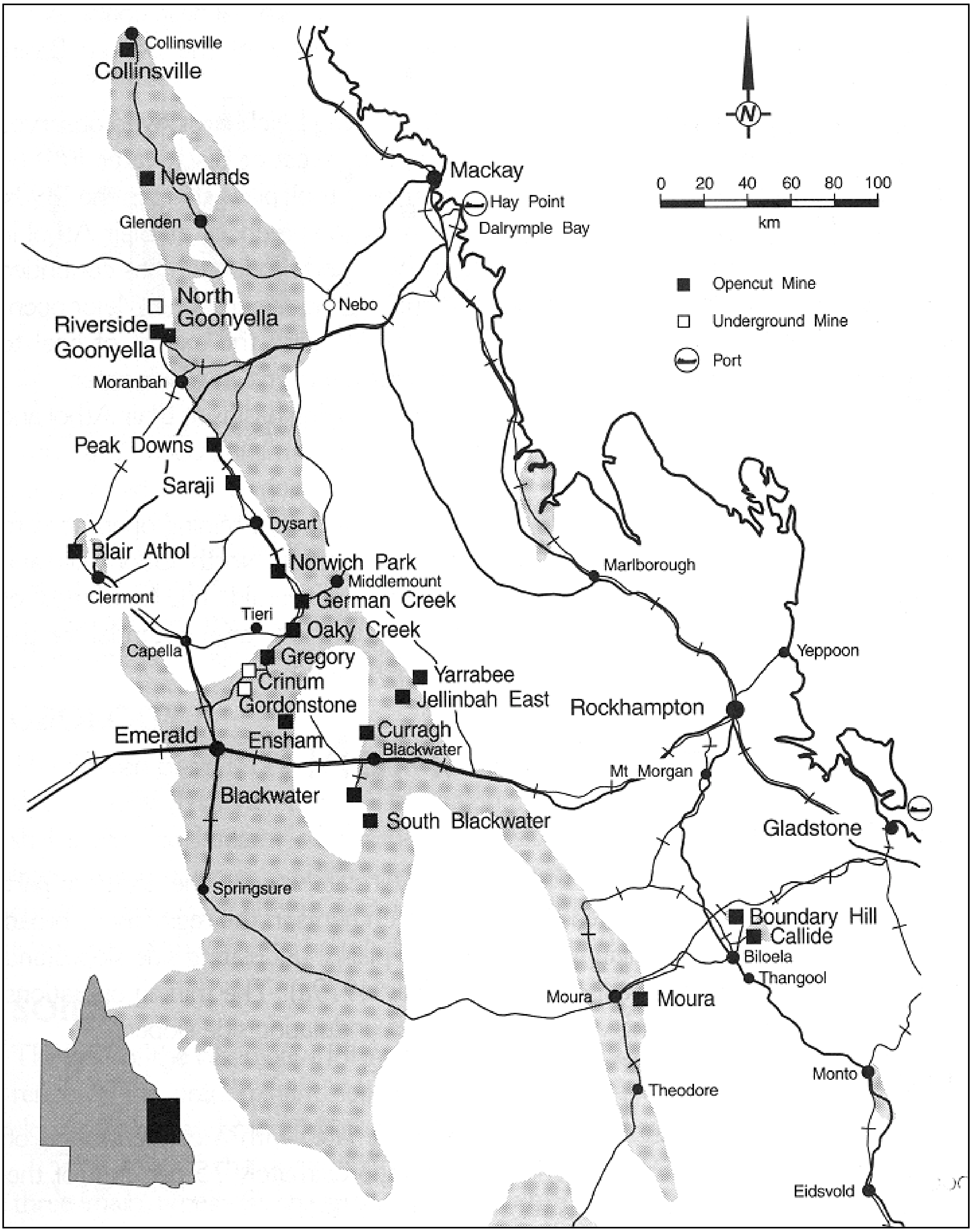


Figure 1. Location of the Bowen Basin and associated coal mines in central Queensland. Source: (Roe *et al.* 1996)

Seeding information available from the Goonyella Riverside mine indicate the inclusion of further species into pasture seeding mixes during the 1990's. These included the improved grasses *Bothriochloa insculpta* cv. Bisset, *Bothriochloa pertusa, Melinis repens* and *Urochloa mosambicensis,* and legume species including *Cassia rotundifolia* cv. Wynn, *Lablab purpureus* and *Clittoria turnatea* cv. Milgarra. Despite the more diverse mixes, buffel and Rhodes grasses remain the major contributors to pasture composition.

Actual rates applied and species mixes vary with practitioner and local conditions, however heavier seeding rates (up to 70 kg/ha combined) are used on more hostile media (Roe *et al.* 1996), or on relatively steeper sites such as batters.

3.4 Species composition

Nearly all documented sites are overwhelmingly dominated by buffel grass. Buffel grass contributed at least 50 % of live cover at more than 80 % of 48 documented pasture sites across Moura, Blackwater, Gregory, Norwich Park and Goonyella Riverside mines. At two thirds of these 48 sites, buffel grass contributed at least 80 % of total live cover.

Rehabilitation pastures are not floristically diverse. Data from species-area curves suggest that up to 25 species may potentially be present in the sward at any one site, but the number of species is controlled to some extent by the presence of buffel grass. In an analysis of vegetation data from Goonyella Riverside mine, Grigg (1999a) found that pattern diversity and species richness were negatively correlated with the level of cover contributed by buffel grass. In this Review, species richness showed a weakly curvilinear relationship with increasing contribution of buffel grass to total live cover (Figure 2), reaching maximum richness where buffel grass forms approximately half the total pasture cover. Above this level, cover and associated large accumulations of dry matter (see Section 3.5) are likely to form considerable barriers to establishment and/or survival by other species. In effect, sites with near-complete ground cover are most likely to be almost monocultures of buffel grass. As the contribution of buffel falls below around 30 %, overall sward cover also declines, suggesting that other factors such as media quality may be limiting.

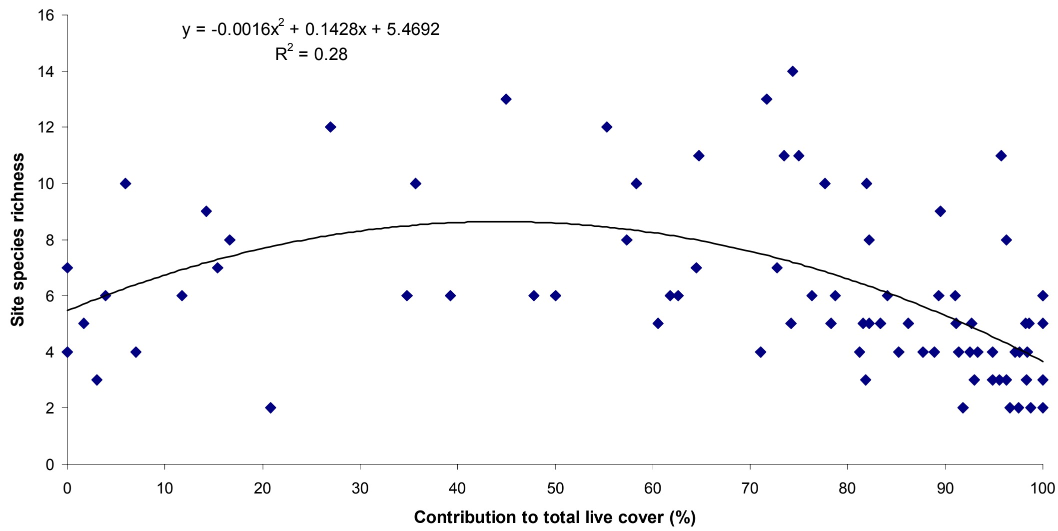


Figure 2. Effect of buffel grass dominance, measured as contribution to total live cover, on species richness of rehabilitated swards (n=80).

Available data on species composition compiled from four mine sites reaffirm buffel grass as the dominant feature of these pastures (Table 1). Various monitoring surveys report an increasing dominance of buffel grass with increasing rehabilitation age and a corresponding decrease in other species. Compiled data on cover contributed by buffel and Rhodes grasses (Figure 3a, b) weakly support such a trend, although seasonal differences cause a high degree of variability. Other introduced or naturalised perennials are also significant (Table 1), although *Urochloa mosambicensis* (Sabi grass) was only recorded on sites at Goonyella Riverside mine. Rhodes grass was observed on around half the surveyed sites, but tends to be more prevalent where water relations are more favourable, such as on fine textured soils or depressions (including the uphill side of contour banks) and waterways. Long-term monitoring data from Peak Downs mine and elsewhere indicate that the proportion of Rhodes grass tends to decline with pasture age (Figure 3b) and is considered to reflect the poorer drought tolerance of the species relative to buffel grass.

Native grasses are not widespread, with only *Heteropogon contortus* (black spear grass) present on at least 10% of sites (Table 1). Where native grasses do occur, they almost invariably form only a small component of the total sward.

Siratro, the closely related *Macroptilium lathyroides* and shrubby stylos are the most common of the sown legumes, with butterfly pea recorded only at Goonyella Riverside mine. The former are more common but are not restricted to areas where moisture collects, and often form sprawling thickets due to the absence of grazing. Leucaena is present at a small number of sites and ranges from scattered individuals to large thickets, but is not regarded as a significant component of these pastures. Siratro appears to be a relatively stable component, with no obvious trends in cover with pasture age (Figure 3c).

The final notable feature is the prevalence of salt tolerant species, including *Atriplex* spp. (saltbushes), *Enchylaena tomentosa* (ruby saltbush) and *Salsola kali*. All species colonise naturally and reflect the widespread occurrence of mildly to strongly saline growth media (Section 5).

Table 1. Species present in pasture-based rehabilitation, ordered according to frequency of occurrence at a total of 40 sites at Goonyella Riverside, Gregory, Blackwater and Moura mines. * indicates introduced or naturalised species.

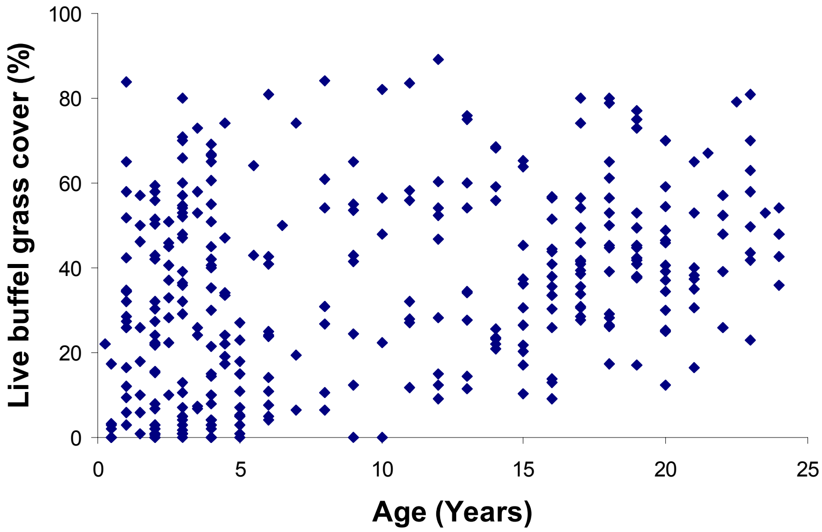
Species		Family	Common name	Occurrence (%)
1. Monocotolydons				
Cenchrus ciliaris	*	Poaceae	Buffel grass	100
Chloris gayana	*	Poaceae	Rhodes grass	53
Urochloa mosambicensis	*	Poaceae	sabi grass	33
Melinis repens	*	Poaceae	red natal grass	15
Heteropogon contortus		Poaceae	black spear grass	10
Panicum maximum var. *trichoglume*	*	Poaceae	green panic	10
Aristida sp.		Poaceae	wiregrass	8
Panicum decompositum		Poaceae		8
Bothriochloa decipiens		Poaceae	pitted bluegrass	5
Astrebla sp.		Poaceae		3
Cenchrus setiger	*	Poaceae	birdwood grass	3
Chloris pectinata		Poaceae		3
Chloris virgata	*	Poaceae	feathertop Rhodes grass	3
Cymbopogon queenslandicus		Poaceae		3
Cynodon dactylon		Poaceae	green couch	3
Dicanthium annulatum		Poaceae	blue grass	3
Echinochloa colona	*	Poaceae	awnless barnyard grass	3
Enneapogon cylindricus		Poaceae	Jointed nineawn	3
Eriochloa pseudoacrotricha		Poaceae	spring grass	3
Setaria incrassata	*	Poaceae		3
2. Dicotolydons				
Legumes				
Macroptilium atropurpureum	*	Fabaceae	siratro	78
Macroptilium lathyroides	*	Fabaceae	phasey bean	25
Stylosanthes humilis	*	Fabaceae	stylo	53
Rhynchosia minima		Fabaceae	rhyncosia	25
Clittoria turnatea	*	Fabaceae	butterfly pea	20
Psoralea tenax				3
Salt tolerant species				
Atriplex lindleyi		Chenopodiaceae	flat-top saltbush	23
Atriplex muelleri		Chenopodiaceae	Mueller's saltbush	10
Atriplex semibaccata		Chenopodiaceae		13
Enchylaena tomentosa		Chenopodiaceae	ruby saltbush	55
Salsola kali		Chenopodiaceae	soft roly poly	30
Sclerolaena muricata		Chenopodiaceae	black roly poly	13
Common pasture weeds				
Abutilon oxycarpum		Malvaceae	flannel weed	10
Sesbania cannabina		Fabaceae	sesbania pea	13
Trianthema triquetra		Aizocaceae	red spinach	10
Galactia tenuiflora		Fabaceae		8
Leucaena sp.	*	Fabaceae	leucaena	8
Peripleura hispidula var. *setosa*		Asteraceae		8

Continued on next page

Table 1. (Continued)

Species		Family	Common name	Occurrence (%)
Corchorus trilocularis		Tiliaceae		5
Einadia hastata		Chenopodiaceae		5
Einadia nutans		Chenopodiaceae		5
Melhania oblongifolia				5
Neptunia gracilis		Mimosaceae	native sensitive plant	5
Pterocaulon serrulatum		Asteraceae		5
Sida filiformis		Malvaceae		5
Boerhavia sp.				3
Chamaesyce alsiniflora		Euphorbiaceae	a spurge	3
Chamaesyce drummondii		Euphorbiaceae	a spurge	3
Crotolaria novae-hollandiae		Fabaceae	New Holland rattlepod	3
Eremophila debilis		Myoporaceae	devil's apple	3
Evolvulus alsinoides				3
Fagopyrum esculentum	*	Polygonaceae	buckwheat	3
Gomphrena celosioides	*	Amaranthaceae	gomphrena weed	3
Grewia latifolia		Tiliaceae	dysentery plant	3
Malvastrum americanum	*	Malvaceae	spiked malvastrum	3
Petalostylis labicheoides		Fabaceae	butterfly bush	3
Portulaca oleracea		Portulaceae	pigweed	3
Pterocaulon sphacelatum		Asteraceae		3
Sclerolaena tricuspis		Chenopodiaceae	giant redburr	3
Sida brachypoda		Malvaceae		3
Solanum americanum		Solanaceae		3
Solanum nigrum	*	Solanaceae	black-berry nightshade	3
Streptoglossa odora		Asteraceae		3
Tridax procumbens	*	Asteraceae	tridax daisy	3
Walltheria indica				3
Zornia sp.		Fabaceae	two leaf pea	3

(a)



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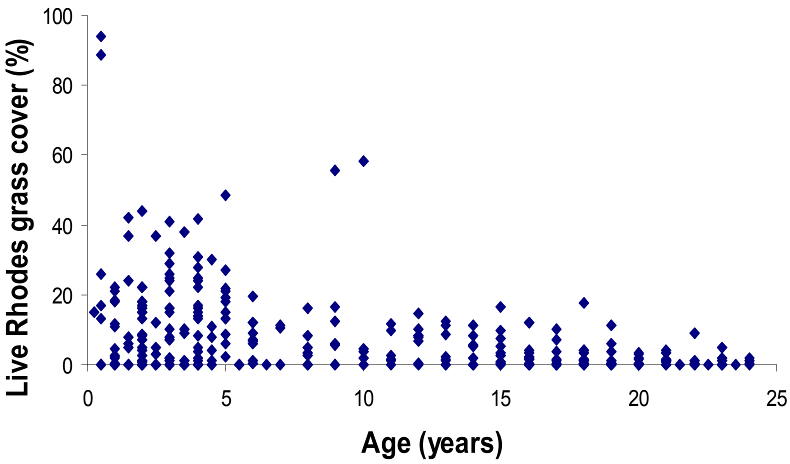

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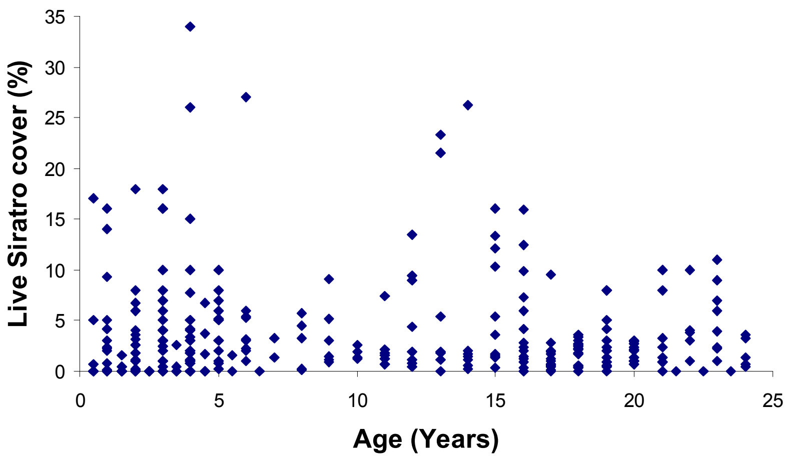

Figure 3. Recorded live ground cover (%) of (a) *Cenchrus ciliaris*, (b) *Chloris gayana* and (c) *Macroptilium atropurpureum* in rehabilitation pastures of varying age. Note the change in scale for (c).

3.5 Cover, basal area and levels of dry matter accumulation

Cover data indicate that it is possible for pastures to establish rapidly after seeding. More than 80% cover has been recorded from rehabilitation only six months after establishment (Figure 4), although these particular sites were hydromulched and heavily seeded. Pastures established for more than 10-15 years indicate consistently high levels of total cover, a large proportion of which is accumulated standing and detached litter (see below).

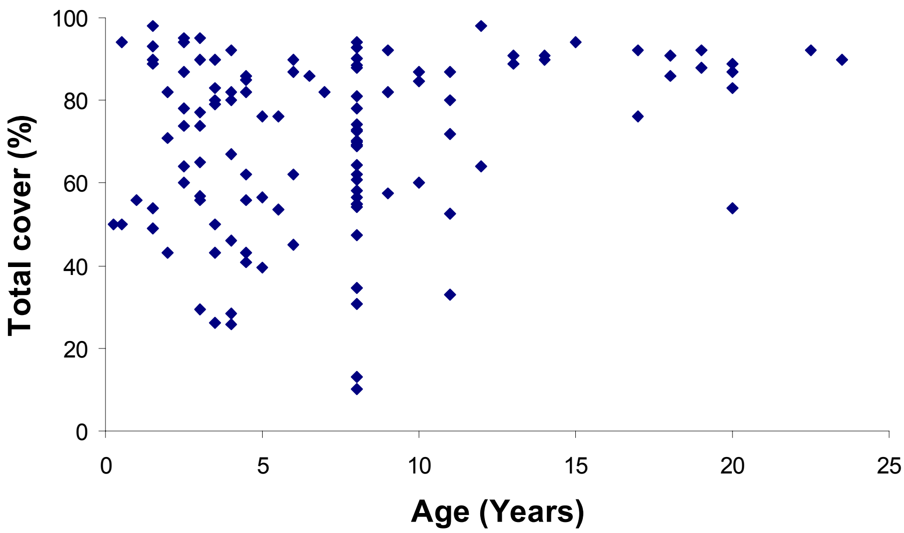

Figure 4. Recorded total projective ground cover (including litter) in rehabilitation pastures of varying age.

Figure 4 indicates that while satisfactory levels of cover are possible within a relatively short time, some pastures may take many years for cover to fully develop. Data available from long-term monitoring transects at Peak Downs mine (Figure 5) show that levels of standing cover (live and standing litter) may remain less than 50 % for up to 15 years after establishment. In these cases, pastures were sown directly into bare spoil material, and performance might be regarded as inferior to pastures established under present rehabilitation methods using replaced topsoil. These data are also confounded by a lack of information on the detached litter component which would increase the overall levels of ground cover. However, the results do suggest the potential importance of litter for surface cover and erosion control in these systems.

Figures 4 and 5 indicate that there is no discernible decline in either total cover or cover contributed by buffel grass with pasture age up to a maximum of 25 years since establishment. Concerns have been expressed at the longer-term persistence of these pastures with nutrient rundown as a result of soils with typically low CEC.

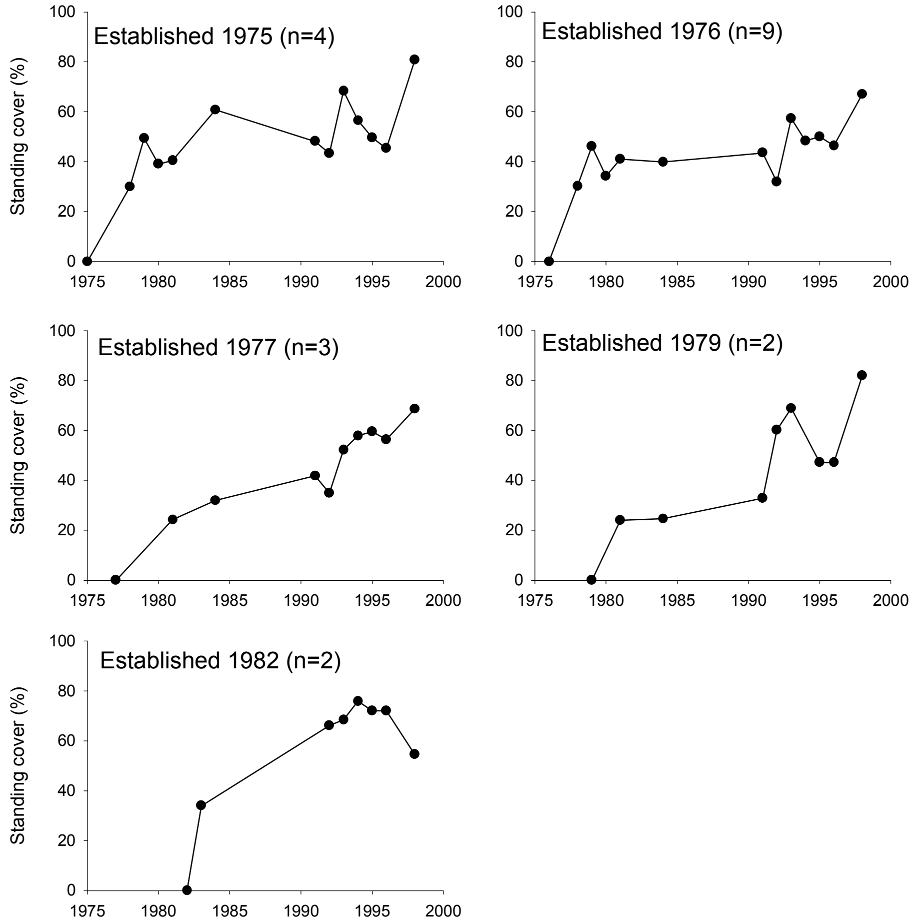

Figure 5. Long-term changes in standing material (excluding detached litter) in pasture-based rehabilitation at Peak Downs mine.

The relationship between projective cover and above-ground dry matter is curvilinear, with complete cover afforded only with very high accumulated dry matter (Figure 6). Similar relationships exist for pastures in non-mined areas (Scanlan and McIvor 1993), but the levels of accumulated dry matter on rehabilitation pastures are rare in the pastoral context. Dry matter levels might be regarded as excessive with respect to potential losses of nutrients and organic matter in fire. At the lower range of dry matter, small decreases in site dry matter correspond with relatively large increases in the amount of bare ground. There are clear implications for surface stability with the re-introduction of cattle to these systems.

Plant basal area, or surface contact cover, is generally less than 10 % across surveyed sites, reflecting the tussock nature of the dominant buffel grass. The relationship between basal area and total ground cover is again curvilinear (Figure 7), but a large range of basal areas exist for higher (total) cover levels, most probably due to the presence of accumulated detached litter.

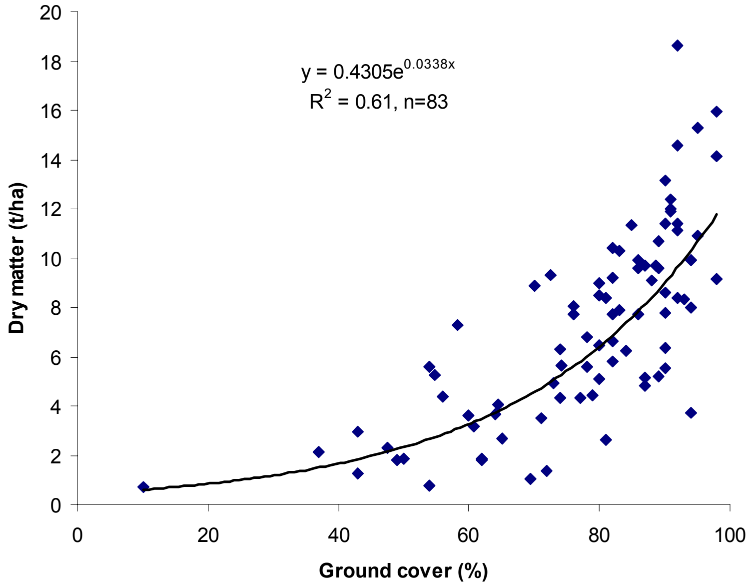

Figure 6. Relationship between projective total ground cover (including litter) and above-ground dry matter in rehabilitation pastures. Data are from established pastures or experimental plots of 3 - 23 years of age across Moura, Blackwater, Gregory, Saraji and Goonyella Riverside mines. Dry matter includes detached and standing litter.

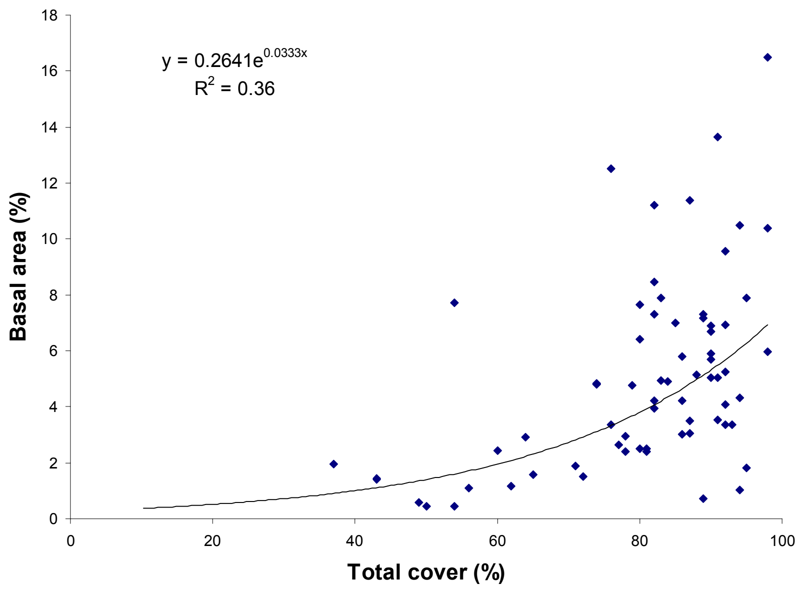

Figure 7. Relationship between projective total ground cover (including litter) and basal area.

3.6 Sward productivity

There are currently no specific data available on primary productivity of rehabilitation pastures in central Queensland. Inherent productivity will be a function of media properties, site characteristics, pasture age and pasture composition. Under favourable rainfall conditions, a 6-year old pasture at Goonyella Riverside mine produced up to 4.7 t/ha over a 2.5 month period following a burn in December (Carroll and Tucker, unpublished data). This is likely to be in the upper range of expected values. Willcocks and Filet (1993) reported a growing season yield of 6.6 t/ha for a buffel grass pasture growing on a brigalow clay soil, although productivity of sown pastures is known to decline with time since establishment.

An estimate of productivity can be derived from changes in above-ground dry matter with rehabilitation age (Figure 8). The fitted logarithmic model indicates relatively high productivity initially, with a rapid decline thereafter such that dry matter accumulation is slow after approximately five years. Clearly, there are other factors involved which weaken the relationship with age. However, these data parallel pasture behaviour on unmined lands where productivity declines are commonly observed after 5-7 years, particularly on soils of lower fertility (Graham *et al.* 1985). Mean rates of dry matter accumulation in the initial 2-3 years on rehabilitation pastures are comparable with the production levels reported by Willcocks and Filet (1993), particularly when decomposition is taken into account, but there is an obvious range in performance. This will be dependent on growth media properties, establishment conditions, fertiliser regimes applied and seeding rates. In ageing pastures where moisture is adequate, growth is principally limited by the supply of N through decomposition and internal redistribution, and the declining slope after 5-10 years shown in Figure 8 may be related to a restriction in N supply resulting from immobilisation in standing and detached litter, roots and microbial biomass (Robbins *et al.* 1989, Robertson *et al.* 1993, 1995).

Figure 8 suggests that there is no apparent degradation in these pastures that may be due to nutrient rundown (as distinct from nitrogen immobilisation), at least up to approximately 25 years since establishment. This is supported by data on basal area changes with age (Figure 9), which show no apparent contraction with the age of the rehabilitated site.

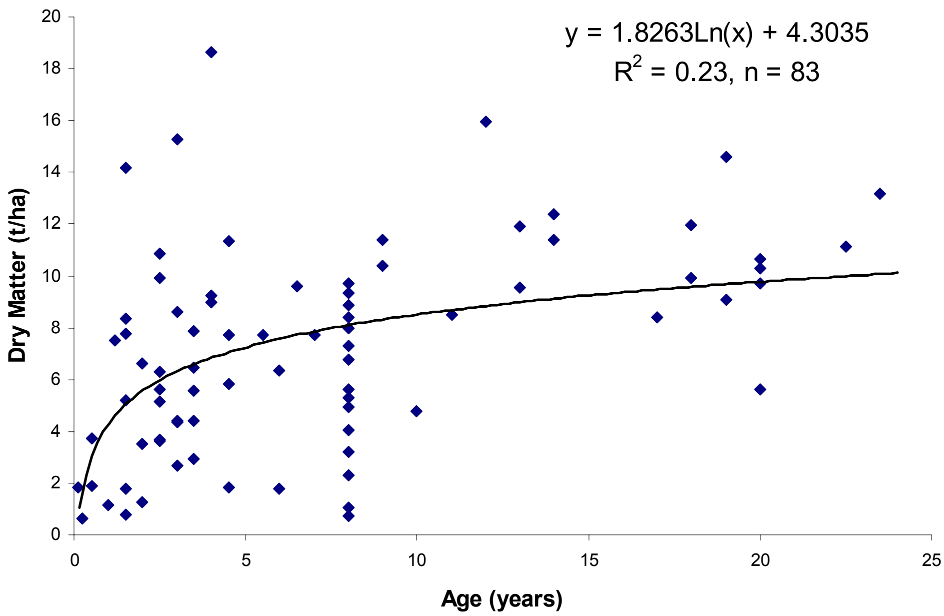

Figure 8. Changes in above-ground dry matter with age of rehabilitation pasture.

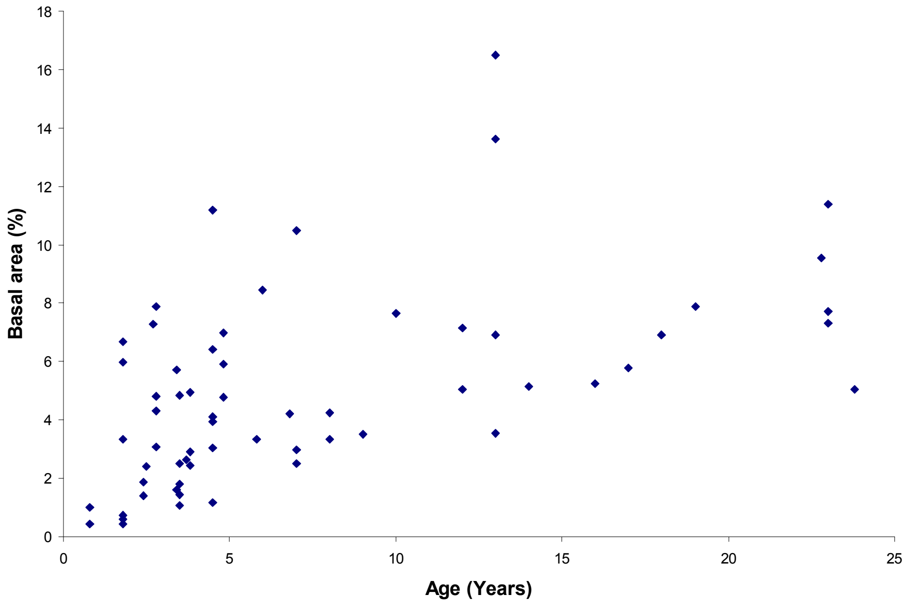

Figure 9. Changes in basal area (%) with age of rehabilitation pasture.

3.7 Forage quality

Limited data are available on dry matter digestibility and nutrient contents of rehabilitation pastures. Analysis results of grab samples from 22 pasture-dominated monitoring sites at Goonyella Riverside mines are provided in Table 2 (Grigg 1999a, Grigg 2000).

Table 2. Pasture forage quality analyses of pluck samples collected in March 1998 and September 1999 from 22 rehabilitation pasture sites at Goonyella Riverside mines.

Parameter	Units	March 1998		September 1999		Cattle requirements*
		Mean	SE	Mean	SE	
DMD	(%)	50.2	(0.97)	48.7	(0.78)	
CP	(%)	7.7	(0.70)	8.5	(0.49)	7-10
N	(%)	1.23	(0.11)	1.35	(0.08)	1.0
P	(mg/kg)	2739	(213)	2511	(224)	1800-3200
K	(%)	2.89	(0.15)	1.40	(0.07)	0.5
Ca	(%)	0.61	(0.04)	0.67	(0.08)	0.19-0.40
Mg	(%)	0.29	(0.02)	0.37	(0.02)	0.19
S	(mg/kg)	1369	(87)	589	(81)	1500
Na	(mg/kg)	4460	(1473)	8360	(2189)	800-1200
Fe	(mg/kg)	563	(105)	675	(121)	40
Al	(mg/kg)	566	(126)	873	(147)	NR
Cu	(mg/kg)	4	(0.4)	9	(0.6)	7-10
Mn	(mg/kg)	102	(11)	135	(12)	15-25
Zn	(mg/kg)	31	(2)	32	(7)	20 - 30
B	(mg/kg)	14	(2)	19	(2)	NR
Co	(mg/kg)	1.3	(0.1)	3.3	(0.4)	0.11
Se	(mg/kg)	2.0	(0.3)	4.5	(0.4)	0.05

* SCA (1990), NR = no recommendation.

Dry matter digestibility (DMD) is low but typical of tropical grasses throughout Queensland (Minson 1990) and consistent with results for *C. ciliaris* reported elsewhere (Dalzell *et al.* 1995). Total N and crude protein contents are also poor, reflecting low available N in the reconstructed soils. Protein contents of 7 % and N concentrations of at least 1 % are considered minima for maintaining adequate rumen function, with more than 10 % crude protein considered desirable for animal weight gain (SCA 1990). In this regard, N inputs from the legume component will be relatively important in improving dietary intake. Nitrogen fixation by legumes is likely to be minimal where available P falls below 8 mg/kg (G. Bourne, pers. comm.).

In terms of mineral nutrition, the biggest problems appear associated with a marginal Cu content, although Cu levels were also low in an adjacent buffel grass pasture on unmined land (Grigg, 1999a). In addition to low total reserves, high Fe and Al concentrations in many samples may adversely affect the bioavailability of Cu. While it is highly likely that at least some Fe in these samples is from soil contamination (Fe was inversely related to total ground cover at each site), and therefore not necessarily at toxic levels *per se*, it is recommended that Fe intake should not exceed 500 mg / kg (SCA 1990).

Possible deficiencies are evident for S. Supplementary feed in lick form containing urea, S, P, Na and trace Cu would alleviate most deficiencies, but the resulting increased feed intake needs to be balanced against pressures on retaining an adequate ground cover for site stability.

Cobalt and selenium were investigated as these elements are critical in the synthesis of vitamins B_{12} and E, respectively. For Co, most concerns relate to deficiencies which can cause loss of appetite, wasting of musculature, and death. The results presented indicate that the element is abundant across all mined and unmined sites, with samples containing abundant Co most probably due to soil contamination, similar to Fe. Cattle can apparently tolerate dietary levels well in excess of requirements and there appears little concern of toxicity. Similarly, Se is tolerated at levels in excess of requirements and symptoms of toxicity reportedly appear with sustained ingestion of diets containing 5-40 mg Se / kg dry matter (SCA 1990).

3.8 Post-establishment management of pastures

At the commencement of this Project, operational cattle grazing was absent from rehabilitation pastures, and grazing end-uses nominated within Agreement Acts and lease conditions remained largely untested (Roe *et al.* 1996). Aside from remedial works on obviously failed areas and irregular fertiliser application, rehabilitation pastures generally receive little attention after establishment. This contrasts with operations in the Hunter Valley coalfields where cattle are reintroduced, on the larger operations at least, 18 months to two years after establishment (Hannan and Gordon 1996).

4.0 SURFACE STABILITY

4.1 'Acceptable' levels of erosion

The creation of a stable land surface is fundamental in achieving sustainable post-mining land uses and in limiting off-site impacts. Control of erosion (the loss of soil through sheet, rill and gullying processes) is therefore of paramount importance, but there remains debate over what is an acceptable level of erosion. Lang and McCaffrey (1984) considered that for continued pasture productivity, the rate of soil loss should not exceed the rate of soil renewal, estimated to be in the range 0.2-1.2 t/ha/year based on natural rates of soil removal and assuming an equilibrium exists between soil renewal and erosion. Initial rates of soil structure development from mine waste rock could be higher, due to the exposure of readily weatherable materials to the subaerial environment (Fitzpatrick *et al.* 1995) and rapid development of a vegetation cover with associated effects on soil biological activity. Observations made on fine sandstone overburden from coal mines in the Hunter Valley, for example, suggest soil formation rates in the order of 3-4 t/ha/year (Lang and McCaffrey 1984). While accurate rates of soil formation are not available for central Queensland minesoils, it is clear that the parity between soil loss and the rate of overall profile improvement becomes critical for reconstructed mine soils with underlying materials that are hostile to plant growth. In these cases, loss of the capping layer will progressively reduce vegetation performance and ultimately lead to failure.

4.2 Reconstructed landforms supporting pastures

Open-cut mining operations utilising draglines typically create parallel spoil piles with slopes of up to 75 % (angle of repose). For pasture-based rehabilitation, these spoil piles are recontoured to lower slopes of around 15 % (Russell 1979, Bell 1984), but can be up to 25 % if physical limitations exist, such as proximity of haul roads, significant remnant vegetation or lease boundaries. Where pre-stripping operations are carried out as part of the mining process, materials are typically dumped within dragline spoils to produce plateau areas with design slopes of approximately 3 %. However, in both dragline and pre-strip landforms, the 'boxcut' slope where excavation initially commenced is usually the steepest slope. With few exceptions, the final landforms also remain elevated relative to the pre-mining landscape due to a spoil swell factor of approximately 20-30 % when disturbed (Bell 1984, Elliott and Reynolds 2000). Resulting landforms are more exposed and are less able to retain moisture, resulting in potentially higher levels of runoff. Post-mining landforms are therefore at a relatively heightened risk of erosion (Bell 1984, 1996).

This Review is restricted to consideration of 'standard' pasture-based rehabilitation which has been established on regraded or designed slopes of less than 30 %. 'Ponded' or terraced landforms which contain angle of repose slopes, even where these have benches revegetated with pasture grasses, are regarded as unsuitable for grazing purposes due to limitations of access and extent of areas that could potentially be grazed, and are not considered.

4.3 Effect of vegetation on soil loss

There exists considerable evidence from minesite erosion research and elsewhere that the single most important factor affecting soil loss in rehabilitated pastures is vegetation cover. Evidence is available from small-scale rainfall simulator studies (Loch and Orange 1997, Loch and Pocknee 1998, Loch 2000a), field plots (Silburn *et al.* 1992, McIvor *et al.* 1995, Carroll *et al.* 2000) and larger scale (0.5 ha) catchment studies (Carroll *et al.* 2000, Carroll and Tucker 2000).

Vegetation affects potential soil loss by improving infiltration where this may be affected by surface sealing or poor structure, particularly over the first 5-6 years from establishment (Loch and Orange 1997), providing surface protection from raindrop impact and reducing the velocity of overland flows. Loch and Pocknee (1998) considered the effect of vegetation on infiltration to vary with the maturity of the site (time elapsed since establishment), the type of vegetation and properties of the soil. However, the vegetation effect is marked and measurements of infiltration parameters (and hence runoff) made on fresh materials will greatly underestimate soil hydraulic conductivity (Loch and Orange 1997), and hence overestimate potential erosion rates in established pastures. Loch (2000a) concluded that at low levels of cover, infiltration was probably improved through a reduction in surface sealing and water-repellence (on a grey sandy loam topsoil), while in the higher cover range, root development assisted in improving soil structure through aggregation and in the formation of stable macropores or root channels (Loch and Orange 1997). Wetting patterns have been observed to be closely associated with grass clumps (Loch 2000a). McIvor *et al.* (1995) also suggest that the development of a vegetative cover encourages faunal colonisation and therefore the level of bioturbation.

Vegetation reduces the amount of runoff through improved infiltration, such that there is less overland flow to convey sediment. The cover elements also impede overland flow by diverting flow around the obstruction, thereby reducing flow velocity and hence the ability to carry sediment. Simple removal of the cover will have variable effects depending on the size of the rainfall event. McIvor *et al.* (1995) found that for small rainfall events following a fire in grazed pastures, runoff and soil loss were lower than expected. They concluded that the existing infiltration capacity of the pasture (which remained intact following a fire) was able to absorb the incident rainfall. However, for larger events where the infiltration capacity was exceeded, runoff and soil loss patterns mirrored those for pastures with low inherent cover.

4.3.1 'Safe' level of cover

The response of erosion to increasing cover is curvilinear (Figure 10), due to soil removal being principally by rill formation at low cover levels, but only by interrill processes (sheet erosion) at high levels of cover (Loch 2000a, Loch 2000b). In studies at Meandu mine, Loch (2000a) concluded that 'as a rule of thumb', a minimum cover of 50 % is required to reduce soil loss to negligible levels. Similar levels of cover have been reported as being the minimum necessary to effectively reduce erosion losses under conditions of natural rainfall in Queensland (McIvor *et al.* 1995, Carroll *et al.* 2000, Carroll and Tucker 2000). Data from monitoring studies on rehabilitation pastures support these experimentally-derived results. Figure 11 shows that soil loss from existing rills was significantly reduced for cover levels > 50 %, although slightly higher cover levels may be desirable. These data were from sites ranging in age from 1 to >20 years since establishment, on a range of materials and slopes up to a maximum recorded of 26 %, reinforcing the importance of a vegetative cover in determining erosion.

In the Hunter Valley of N.S.W., coal mines typically set objectives of maintaining a minimum of 70 % cover (Hannan 1995) for rehabilitation and grazed pastures, based on mine research (Dyson *et al.* 1987) and earlier work in pastoral lands (Costin 1980, Lang and McCaffrey 1984) that demonstrated the effectiveness of this cover level. Selection of a higher level of cover relative to the findings in Queensland may be due to differences in growth habits of the major pasture species. Various studies (e.g. Lang 1979, Lang and McCaffrey 1984, Loch 1997, 2000a) note that variation in potential erosion is greatest at intermediate (20-60 %) levels of cover (Figure 12), being dependent on the size and physical arrangement of surface cover elements to effectively prevent rill formation and reduce interrill erosion. Large elements (0.3-0.6 m diameter) are considered better able to divert and impede overland flow, implying that surface litter could play an important role (Loch and Pocknee 1998).

While useful as threshold targets for vegetative cover, it is emphasized that levels of 50 % cover for Queensland conditions should be regarded as the minimum required rather than the level at which erosion ceases to be a problem. McIvor *et al.* (1995) state that the minimum level of cover would still allow significant losses of suspended sediment in large (but infrequent) rainfall events. Given that the post-mining landforms are generally at greater risk of erosion that the pre-mining state, and that retention of the surface layers may under certain circumstances be crucial for sustained vegetation growth, management of rehabilitated pastures should probably aim to maintain levels of cover higher than 50 %.

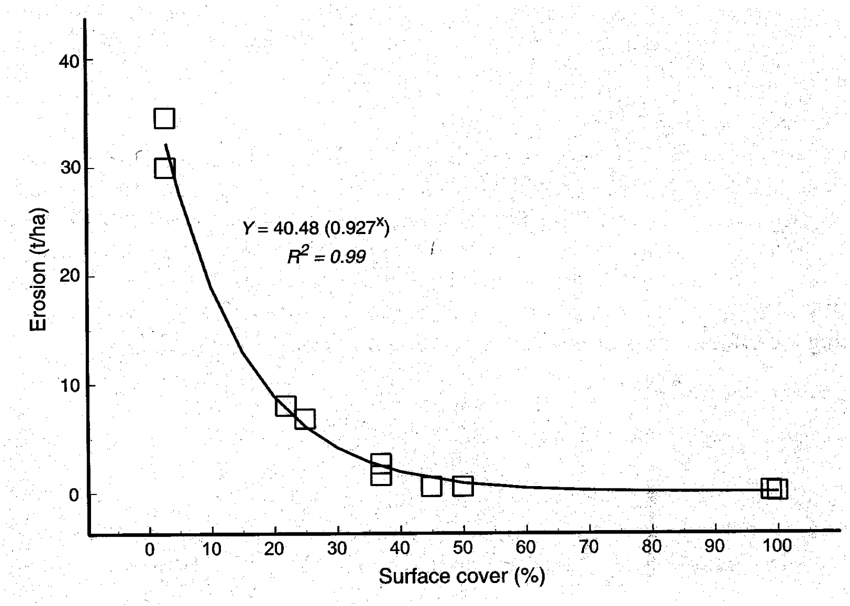

Figure 10. Curviliner response of soil loss to surface vegetative cover on rehabilitation pastures at Meandu mine, Tarong. (Source: Loch 2000a).

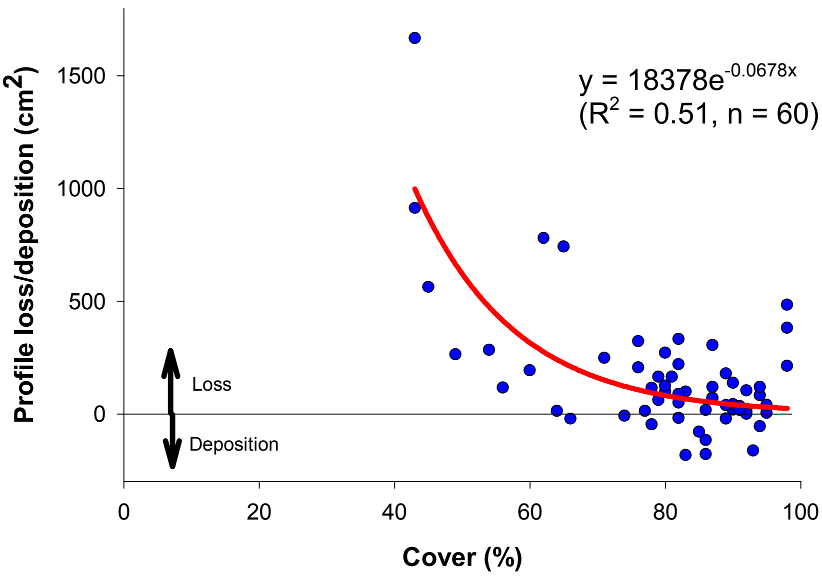

Figure 11. Observed soil movement (cross-sectional area under a fixed horizontal bar of 2 m width) within established rills over 1-2 years in relation to vegetation cover on rehabilitation pastures across four mines in central Queensland.

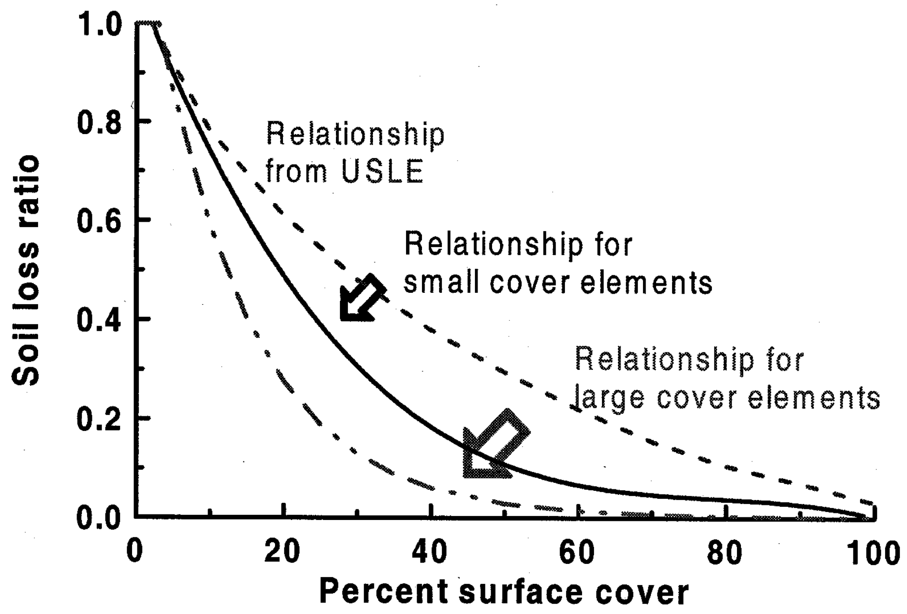

Figure 12. Variation in the soil loss ratio (soil loss relative to loss from a bare exposed slope) with type of surface contact cover. (Source: Loch and Pocknee 1998).

4.3.2 'Window of risk'

Pasture rehabilitation is at greatest risk of erosion in the early establishment phase when cover levels are low (Loch 2000a, Carroll *et al.* 2000). Rehabilitation practices and selection of growth media which assist infiltration, reduce runoff and promote a rapid development of vegetation will therefore significantly narrow this 'window of risk'.

For established pastures, the risk of erosion may be greatest in spring or early summer when thunderstorm activity increases with the onset of the wet season but vegetation cover is lowest at the end of the dry season, particularly if cattle have been reintroduced.

4.4 Other factors affecting soil loss

The Universal Soil Loss Equation is used to predict soil loss from a number of factors. The effect of vegetative cover has already been considered. Other factors include slope gradient and length, inherent erodibility of the material, and the modifying effects of surface conservation practices. These are considered in turn with respect to experimental work and patterns observed from monitoring data. Experimental results considered in the Review are largely drawn from research by So *et al.* (1998) and related publications under ACARP Projects C1629, C4011 and C5009.

4.4.1 Slope gradient

On pasture-based rehabilitation, the effect of slope is secondary to the cover effect. At the plot scale, Carroll *et al.* (2000) demonstrated that erosion from slopes of even 30 % can be reduced to < 0.5 t/ha. However, Loch and Pocknee (1998) reported that greater levels of cover are required on steeper gradients for effective erosion control, and Carroll *et al.* (2000) note that *slopes of increasing grade become progressively more difficult to revegetate*, taking longer to attain the minimum levels of cover needed and losing more soil during that time. At very steep slopes, for example of 75 % or angle of repose, vegetation may fail to successfully colonise and the slope remains unstable (e.g. Grigg 1999b).

Erosion monitoring data from permanent pin apparatus suggest that erosion activity can increase substantially at slopes above 12-15 %, despite the presence of high levels of cover (Figure 13). Based on experience, Russell (1974) considered the 'ideal' slope for rehabilitation in central Queensland to be approximately 10 %.

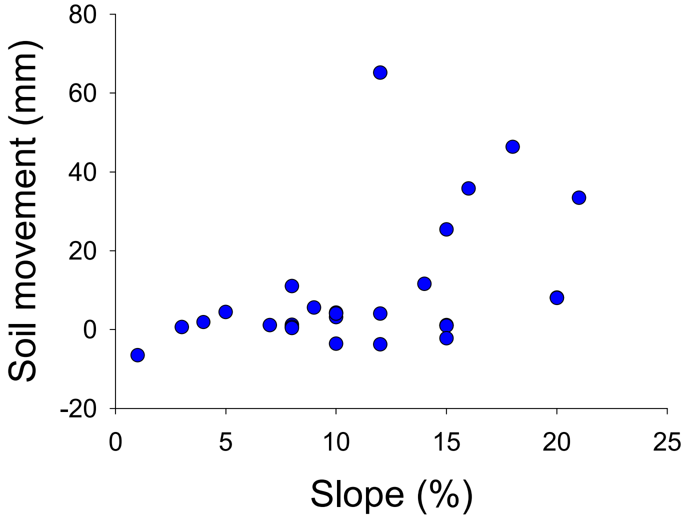

Figure 13. Impact of slope gradient on soil movement for established pasture-based rehabilitation sites. Data are annual changes in the surface profile under a permanent pin apparatus, expressed as average depth in mm across the profile width, over a four year period. Sites are limited to those with a minimum 70 % vegetation cover. Negative soil movement indicates deposition.

There are interactions between slope gradient and media type, both in terms of the inherent erodibility of the material, and in its ability to promote and support vegetative growth. Further analysis of erosion data depicted in Figure 13 indicated that soil movement (at cover levels of at least 70 %) could be more accurately described by a combination of slope and rootzone salinity (Figure 14). Salinity may be acting as a surrogate for factors affecting infiltration and therefore runoff, and is investigated further in Section 5. The fitted curve is exponential, indicating that slope effects are magnified in situations where factors affecting infiltration (such as dispersible materials) are present.

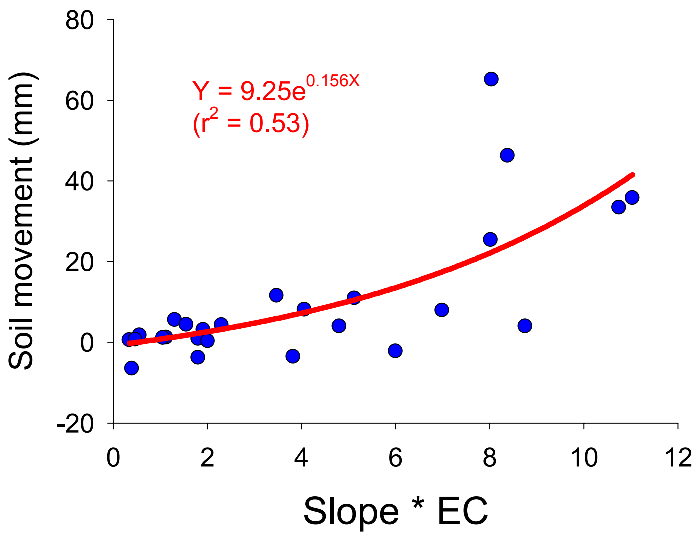

Figure 14. Relationship between soil movement and the interaction of slope with media type (as expressed by rootzone salinity). Soil movement data are those used in Figure 13.

4.4.2 Slope length

Similar to slope gradient, the effect of slope length is reduced once a satisfactory level of cover is attained. Loch (2000a) found that erosion was negligible from simulated slopes of up to 70 m in length where vegetation cover was greater than 50 % cover. The effect of slope length on erosion will therefore be greatest when pastures are establishing and cover levels are low. Management strategies which shorten slope length and/or increase surface roughness (Section 4.4.3) will assist in minimising soil losses during this period.

Slope length information is not routinely collected with data from permanent pin erosion monitoring, and no investigation of slope length effects from field sites could be made.

4.4.3 Surface roughness

McIvor *et al.* (1995) suggested that in rangelands with typically low slope gradient and high surface roughness, velocity and depth of overland flow do not consistently increase with distance down the slope. Further, they suggested that soil loss from these systems was controlled by supply capacity rather than transport capacity.

In rehabilitation pasture systems of relatively steeper grade, Carroll *et al.* (2000) reported that surface roughness also had a pronounced effect on surface runoff. Measured as the ratio of surface distance to slope length, they found that a roughness factor of around 4 reduced runoff to very low rates, regardless of slope gradient. They noted, however, that measured roughness was only meaningful in the early establishment phase prior to rill initiation and/or vegetation development. High initial surface relief will dissipate with time and surface preparation techniques cannot be relied upon to contribute to longer-term sustainability.

Surface preparation for water retention purposes needs to balanced against suitable seedbed conditions for successful establishment. Redistribution of unconsolidated material during storms in steep ridge-furrow micro-relief, for example, has been observed to cause burial of seed to depths at which emergence cannot take place and the burial of new germinants (e.g. McCallum and Grigg 1999).

4.4.4 Media characteristics

The inherent erodibility of materials will have greatest impact during the 'window of risk' prior to or early after establishment, when the materials are relatively unconsolidated and the amount of material exposed is greatest. However, media characteristics will also influence the efficiencies of vegetation to control erosion processes. For example, cover obstructions will be less effective for smaller particle or dispersive materials because their ability to remain entrained in overland flow is higher than larger or heavier sediment particles (Loch 2000a). The type of media at the surface will have indirect effects on vegetation performance which subsequently impacts on infiltration, runoff and the degree of obstruction to overland flow. Media impacts on vegetation performance are considered in Section 5.

Experimental work on a range of soils and overburdens from central Queensland (Sheridan *et al.* 2000a, b) found that the two sets of materials displayed different erosion behaviours, and that there were interactions with slope gradient. Topsoils were found to be more erodible than spoils, a pattern similarly observed at the field plot scale by Carroll *et al.* (2000). On steep slopes, erosion is largely by rilling and loss of soil was most strongly controlled by texture (sand content). Sandy, non-cohesive soils were most prone to erosion under the detachment-limited environment. Soils with higher clay and silt contents, especially at the upper range, were associated with hard setting and sealing characteristics and hence lower detachment. Conversely, at low slopes (*c.* 5 %) where interill process predominate and under which overland flow is limited in what can be carried, the presence of dispersible clays, ESP and organic C content (affecting aggregate density) became more important.

Erosion of overburdens at all slopes was mostly interrill, and therefore properties that most affected soil loss did not change with slope gradient. Sheridan *et al.* (2000a) considered that this was related to the higher rock content of overburdens (providing protection against raindrop impact) and the common presence of surface sealing. On the overburdens tested, increasing clay content was positively related to erosion (the reverse of soils), possibly due to interactions between clay content and ESP, however, elevated ESP is not necessarily associated with a high clay content.

4.4.5 Antecedent conditions

Runoff will be greater for soils already saturated or near saturation from prior rains, or where soil water has not been fully utilised by vegetation.

4.5 Effect of fire on surface stability

Runoff and soil loss from burnt areas are not necessarily comparable to bare areas with a similar level of cover. McIvor *et al.* (1995) concluded that while surface cover is removed during fire, the improved infiltration capacity of the soil due to root channels and soil faunal activity remained relatively intact. Burnt plots only began to behave like bare plots under heavier rainfall events where infiltration capacity was exceeded. Results from an experimental burn at Goonyella mine (Appendix I) showed that sediment concentrations in runoff increased after the fire, consistent with increased raindrop impact and sediment detachment. Sediment concentrations declined as the pasture recovered and raindrop impact was reduced, but runoff from burnt catchments was still higher than from the unburnt control. Reinstatement of a layer of detached or collapsed litter layer in contact with the soil surface was much slower than for standing cover, taking up to two years following the burn. Recovery could be expected to take longer if cattle are re-introduced immediately after burning. Elevated runoff could therefore be expected during this time, and it is speculated that on steeper slopes with replaced topsoils where rill erosion processes predominate (Section 4.4.4), increased runoff could lead to rill initiation.

5.0 FACTORS AFFECTING PASTURE ESTABLISHMENT, PERFORMANCE AND PERSISTENCE

5.1 Climate

The success of establishment when seeding operations coincide with adequate rainfall is well recognised by practitioners, suggesting moisture availability as a major factor controlling pasture establishment.

Average rainfall in the region is from 600 to 700 mm annually, however this is variable across the region and from year to year (Davies and Willcocks 1992). Around 60% of this rainfall is estimated to occur in events of less than 10mm, which are unlikely to be adequate for plant establishment or growth (Willcocks 1993). Approximately 75% of the annual rainfall is received in the summer months between November and March, much of which is associated with cyclones, thunderstorms and/or the presence of a semi-permanent trough across northern Australia (Willcocks 1993). As such, rainfall is often received as high-intensity events of short duration and high spatial variability (Kelly 1979). These events produce high runoff and poor infiltration, particularly on the elevated and sloping post-mining landforms, and pose stability problems as well as moisture availability issues.

Annual evaporation exceeds rainfall by a factor of three and is greater than rainfall at all times throughout the year (Roe *et al.* 1996). The greatest deficit between rainfall and evaporation generally occurs between October and December (Willcocks 1993) and is the period of potentially highest plant stress. Conversely, the period from January to April is generally the period of least deficit and is therefore the most favourable time for pasture establishment.

More precisely, the patterns of rainfall events, especially the occurrence of 'follow up' rains, appear to determine establishment success more than the total fall of rain (Harwood *et al.* 1999). Sequences of rainfall events which are able to provide not only adequate soil moisture, but also lowered surface soil temperatures and elevated levels of humidity, and over as extended period as possible, will result in better germination, emergence and establishment. In the semi-arid tropics, McIvor and Gardener (1985) considered that soil must remain moist for at least three consecutive days to allow adequate seedling emergence to occur. Unpublished research has shown that even on soils of good moisture holding capacity, surface moisture will fall below wilting point within three days of a 'typical' storm event (100 mm/hour for 30 minutes), impacting heavily on the survival of imbibed seeds (H. Baiquni, pers. comm.). The successful establishment of introduced pasture grasses compared with native grasses and particularly woody native species in related work was attributed in part to their ability for rapid elongation of the root radical, permitting the growing tip to maintain contact with the receding moisture front.

Average air temperatures for the region reach a maximum of around 34-35°C in summer, and in winter, average minimum temperatures drop to approximately 5-7°C (Willcocks 1993). 'Heatwave' conditions following thunderstorms in spring and early summer are a common cause of establishment failure. Rosenthal and Hammer (1979) showed that the probability of at least one day with a maximum temperature of 38 oC rose to around 50% during most of December. Soil surface temperatures can be much higher than air temperatures, attaining levels potentially lethal to germinating seed. Harwood *et al.* (1999), attributed limited germination in a trial of various pasture grasses to high surface temperatures, recorded at up to nearly 50 ^{o}C for a dark-coloured topsoil during February.

Levels of solar radiation remain fairly constant throughout the year, and are unlikely to be limiting to plant growth (Willcocks 1993).

5.2 Growth media characteristics

5.2.1 Overview

Investigations and studies of the characteristics of growth media present on mine sites in the Bowen Basin were compiled and reviewed by McLennan (1994). Spoil characteristics are closely related to that of the parent rock, and to the original depositional environment. Materials are essentially composed of three main geological units:

1. Cover sequences of Quaternary alluvium and weathered Tertiary sediments, with extrusive basalts in some areas;
2. Triassic sandstone and mudstone sequences; and,
3. Fresh to weathered Permian coal-bearing measures.

The Permian units contain four main coal measures, described from north to south as the Collinsville and Moranbah coal measures, the German Creek formation, and the Rangal coal measures. Spoils from the Moranbah coal measure are generally alkaline, becoming more so in the south towards Saraji mine (pH up to 9.2), with EC values from 0.8 to 2 dS/m. Spoils become more neutral to acid from Norwich Park mine into the German Creek Formation, with generally lower salinities. The Rangal coal measures are the uppermost coal bearing rocks of the Basin, and are generally alkaline (pH 8 to 9.2), sodic and saline. Materials are dominantly fine to medium grained sandstones with typically illite/montmorillonite clay mineralogy, together with siltstones and mudstones.

Tertiary spoils overlying the Moranbah coal measures are commonly neutral to extremely alkaline (pH 7.4 to 9.6), with EC values up to 4 dS/m – higher than the associated Permian materials. Tertiary sediments overlying the German Creek measures are more variable. All materials are highly weathered and leached, with a significant proportion composed of clay-sized particles of typically smectitic mineralogy. As a consequence, slake resistance and shear strengths are low, presenting particular difficulties for rehabilitation.

5.2.2 Spoil variability

McLennan (1994) noted that several workers have recognised that spoil materials are more heterogenous at the mine scale than at the larger coal-measures scale, considered to be due to changes in the local sedimentary environment and variations in the depth of weathering. Incorporation of Tertiary and Permian materials, and general spoil mixing, during the mining and regrading processes further adds to this variability. Russell (1981, in McLennan 1994), for example, undertook grid pattern sampling at three mine sites and found that variation in spoil characteristics was as great at any one site as it was between sites. Heterogeneity is a distinctive feature of rehabilitated sites, impacting on the successful application of rehabilitation practices (Eastment *et al.* 1989).

5.2.3 Salinity

A large proportion of waste rock materials in central Queensland are saline to extremely saline, and strongly alkaline. Unpublished data presented by Spain (1999) from five Bowen Basin mines indicates that nearly 60 % of 272 samples collected were saline ($EC_{1:5}$ > 0.33). Tertiary-derived materials tend to be more saline than those of Permian origin. Bell *et al.* (1991) found that Tertiary spoils from 24 of 25 sites across five mines averaged greater than 0.4 dS/m (Table 3).

In contrast to spoil materials, reclaimed topsoils are less frequently saline (Table 3), although stripping to depth on some soils can result in highly saline subsoils being returned to the surface.

Data collated from established pasture sites (Figure 15) indicate that surface media are generally less saline and more neutral in character than fresh waste rock, reflecting successful establishment on better substrates and the beneficial effects of a vegetative cover on soil properties. However, where pastures have been established on coarse coal rejects, these tended to be more acid (pH ≤ 5.5).

Table 3. Average pH and EC data (1:5 soil/water) for stripped topsoils and Tertiary clay overburden materials collected from pre-strip pits (in situ sampling) or pre-strip dumps for a selection of coal mines in the Bowen Basin. Reproduced from Bell *et al.* (1991).

Mine	Location	Number of samples	Average pH	Average EC (mS/cm)
	Tertiary clay overburden materials			
Goonyella	Broadmeadow Pit	7	8.20	0.456
	Broadmeadow Dump	12	8.64	0.479
	Leightons Dump	6	7.95	2.514
	Cleanskin Dump	15	8.47	0.958
	Redhill Dump BWE	56	8.57	1.371
	Redhill Dump T&S	8	8.36	0.562
Riverside	R23 Pit	11	8.35	1.590
	R5 Pit	10	8.28	1.597
Peak Downs	Boomerang Pit	14	7.44	1.716
	Ripstone Pit	18	8.98	0.730
	Heyford Pit	6	8.27	0.269
	Winchester Pit	5	9.59	0.524
Saraji	Acacia Pit	11	8.58	0.453
	Acacia Dump	8	8.66	0.647
	Bauhinia Pit	21	8.48	0.409
	Coolibah Pit	22	6.63	2.471
	Coolibah Dump	18	7.00	1.747
	Dogwood Pit	1	5.74	0.537
	Ebony Pit	7	7.52	0.472
	Ebony Dump	16	5.91	0.787
	Grevillea Pit	2	6.48	3.390
Blackwater	Stewart Pit	14	9.10	0.614
	Stewart Dump	5	9.05	0.647
	Tannyfoil Pit	8	9.25	0.476
	Deep Creek Pit	16	8.78	0.551
	Topsoil materials			
Goonyella	Broadmeadow	1	8.21	0.056
	Red Hill	1	8.25	1.338
Riverside	R23	1	7.91	0.092
Peak Downs	Boomerang	2	7.81	0.067
	Ripstone	2	7.56	0.076
	Winchester	1	7.99	0.063
Saraji	Acacia	6	8.09	0.157
	Bauhinia	1	8.67	0.078
	Coolibah	2	7.74	0.872
	Dogwood	1	6.87	0.098
	Ebony	1	5.13	0.692
	Grevillea	3	7.86	0.091
Blackwater	Stewart	1	8.96	0.202
	Tannyfoil	2	7.88	0.233

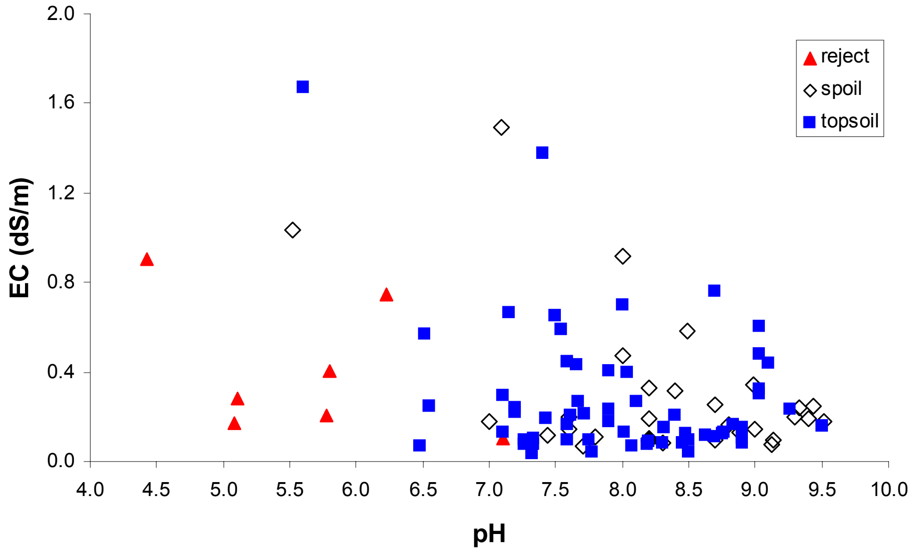

Figure 15. Surface (0-10 cm) EC and pH (1:5 basis), recorded for pasture-based rehabilitation on 7 mines in central Queensland (n=99).

Soil salinity at the surface reduces the level of seedling emergence by slowing germination and thus increasing the time that the growth media must remain moist (Harwood 1998). Salinity also acts to retard plant growth through osmotic stress, and may affect the functioning of root symbionts, and indirectly lower nutrient availability. Salinity acts as a direct constraint to success but also compounds the problem of an adequate moisture supply from rainfall.

Analysis of data from monitoring studies indicates a strong influence of average salinity in the main rootzone, here defined as the upper 40 cm of the reconstructed profile (Jackson *et al.* 1996), on pasture performance (Figure 16). An exponential improvement in total dry matter is evident for decreasing salinity levels. A similar relationship exists when salinity in the whole profile (0-100 cm) was considered, but the correlation was weaker. Consideration of salinity in only the surface 10cm gave an indication of the upper boundary line, but failed to detect the influence of salts at depth such that a range of dry matters were possible where surface salinity was low. Direct relationships between salinity and surface cover were consistently poor, regardless of the depth considered, and this is thought to be due to the confounding effect of increasing litter cover with rehabilitation age, independent of performance. However, using the dry matter – cover relationship derived in Figure 6, and a conservative minimum cover level of 70 % for adequate erosion control (Section 4.3.1), a maximum rootzone salinity of approximately 0.6 dS/m would permit development of sufficient dry matter for surface protection. Such levels, however, do not allow for periodic grazing for which higher dry matter levels are required and hence the 'threshold' salinity should be lower. The levels observed are roughly consistent with published data for salinity tolerance in buffel grass (SalCon 1997), taking into consideration differences due to field conditions and shifts in pasture composition with increasing salinity (greater presence of more salt-tolerant species).

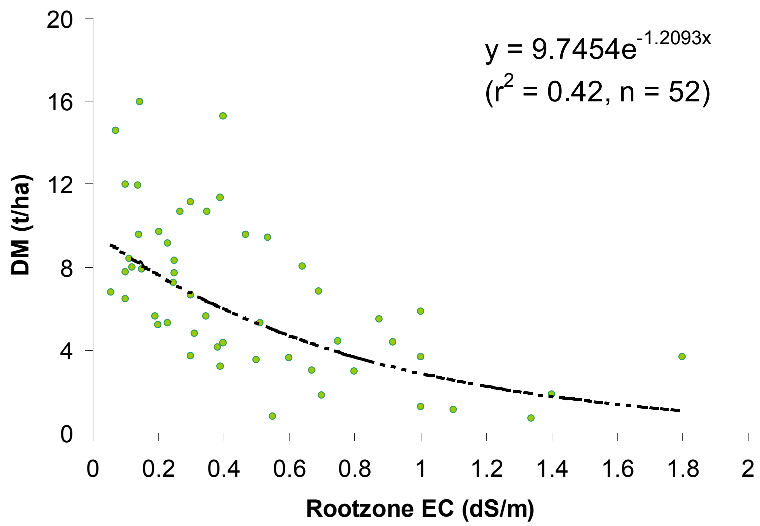

Figure 16. Effect of rootzone (0-40cm) salinity on pasture dry matter (live and litter material).

5.2.3.1 A salinity model for reconstructed soils

Newly established areas of rehabilitation, or *in situ* spoil, are not static in their salinity characteristics. The development of leaching profiles is evident from repeated samplings of the same site in numerous monitoring studies, and in the reduction in maximum rootzone salinities observed in rehabilitated sites of increasing age since establishment (Figure 17).

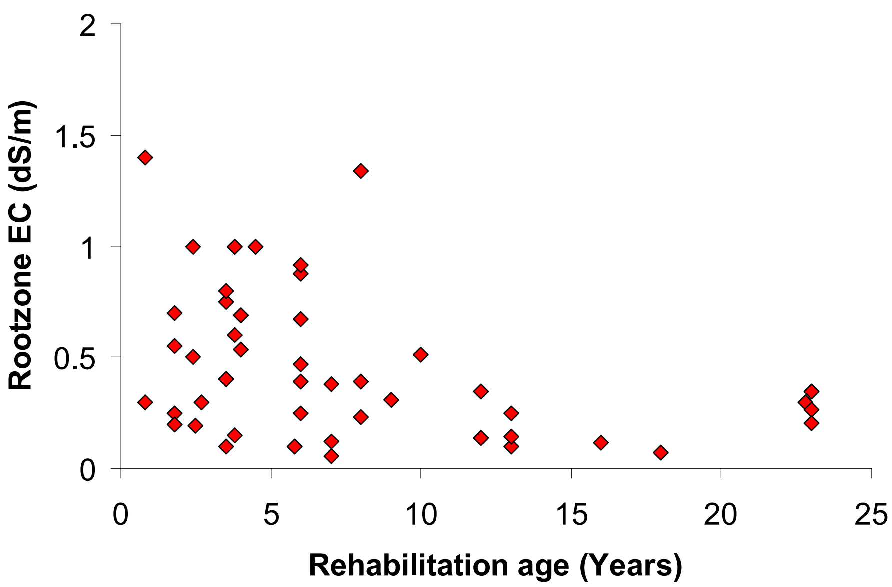

Figure 17. Observed rootzone (0-40cm) salinity (1:5 basis) in pasture-based rehabilitation of varying age.

The development of leaching profiles varies with the nature of the surface materials, and with the development of a vegetative cover and associated biological activity. Loch and Orange (1997) demonstrated improvement in infiltration capacity of a minesoil over the first four years following rehabilitation, driven by re-aggregation and the formation of macropores by plant roots and fauna. Leaching is accelerated by surface materials and surface preparation strategies which assist in the capture of surface moisture and promote infiltration (see also Section 4.4.3). Figure 18, for example, indicates the more pronounced development of a leaching profile under a coarse-textured replaced topsoil compared with the finer textured clay. Highly sodic materials are also well known to pose major problems for salt removal through the formation of surface seals. Experience has shown that saline-sodic materials are particularly difficult to successfully revegetate.

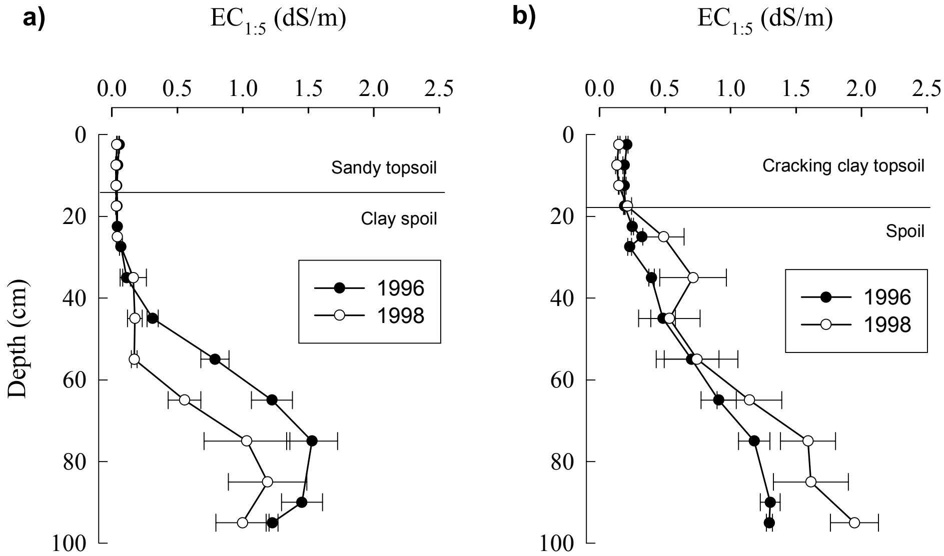

Figure 18. Differences in the development of leaching profiles in approximately 10 year old rehabilitation under a) a coarse textured topsoil and b) a clay topsoil. Both sites were on slopes < 10%.

A preliminary model has been developed that accounts for salt movement in these newly constructed soils, and which has the potential to predict changes in salinity (and hence improvements in grass growth) with time. The model is based on work by Shaw (1995), who described soil salinity as a balance between the capacity for leaching – the rainfall input – and the soils resistance to water movement.

For rehabilitated pastures in central Queensland, rootzone salinity was found to be reasonably well related to several factors: rehabilitation age, being a coarse surrogate for rainfall at each site since establishment; and a function containing clay content, CCR or the ratio of the CEC of the clay fraction to the clay content (an index for clay mineralogy) and ESP or sodium content. The function uses the terms of Shaw (1995) which account for a soil's porosity and the effect of clay dispersion into the pore spaces reducing overall hydraulic conductivity. Salt movement in the soil can thus in effect serve as a tracer for water infiltration and hence the availability of moisture for plant growth. Initial EC forms the final part of the relationship shown below, since establishment conditions are frequently saline but variable (Table 3 and Figure 17). The relationship so far developed is given by:

$$Rootzone\ EC \quad \propto \quad Initial\ EC, \frac{rehabilitation\ age}{\int(clay\ content, CCR, ESP)}$$

Conceptually, the equation can be interpreted as rootzone salinity in pasture-based rehabilitation of a given age is related to its initial salinity level, and the degree of leaching of salts which is in turn determined by rainfall inputs and the soils resistance to water movement. Relationships between the factors require further investigation. However, the model is useful in highlighting the important role of adequate media characterisation and handling in influencing salinity and hence in likely pasture performance. Lower initial salinity will enhance early grass establishment, reducing the erosion risk, and accelerating vegetation-induced improvements to soil structure. The model probably has greatest value in being able to predict, for a given set of soil properties, the likely improvement in salinity over time and thus the improvement in site quality for pasture growth with time. Such a tool may assist in lease relinquishment long before lowered salinities are actually attained.

Further work is needed to refine the models developed from the limited dataset available. Evaluation and integration of factors that influence *effective* rainfall input, for example, including slope gradient, surface roughness (not currently recorded in monitoring) and the modifying effects of a developing vegetation cover on infiltration, are required to increase the accuracy of prediction.

5.2.4 Fertility

The effects of fertility in the collated dataset were obscured by the over-riding effects of salinity. However, when confining investigations to sites with rootzone salinities of less than 0.4 dS/m, thereby effectively removing the salinity limitation from the analysis, soil fertility was found to be important (Figure 19). Total dry matter was positively related to the amount of plant-available P, a relationship that was improved with the addition of total sand content into the equation. This latter was found to be closely (and negatively) related to the CEC of the material (which is mainly associated with the silt and clay fractions), and hence the availability of major cations for plant growth. Available P could be substituted with soil N, suggesting a similar influence of N on grass growth. Regression equations containing both N and P were not significantly better at predicting dry matter than either nutrient alone.

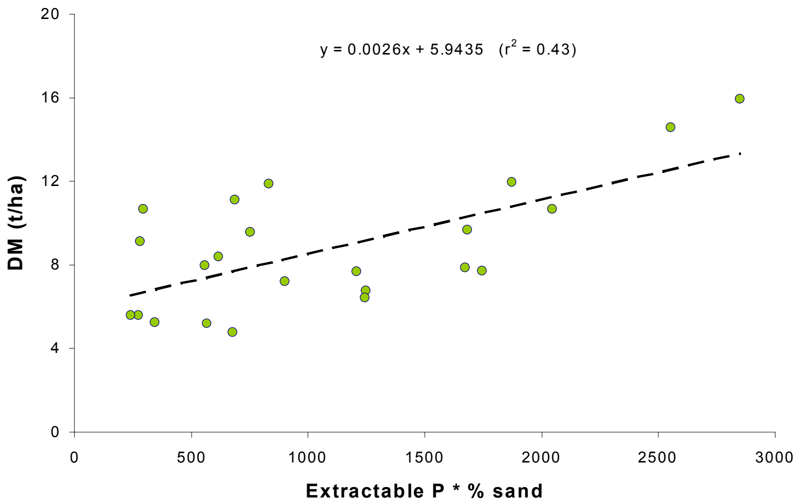

Figure 19. The response of rehabilitated pastures to soil nutrients at sites with rootzone EC < 0.4 dS/m. Sand content was negatively related to CEC.

Many rehabilitation monitoring sites examined contained surface media with low to very low CEC, comparable to the poorer soil types in the region. While surface characteristics alone do not determine site fertility, they do provide a reasonable prediction of site quality in the longer term since CEC determines the capacity for nutrient retention against leaching losses.

5.2.4.1 Fertiliser usage

Fertiliser use varies considerably from mine to mine, and also over time with changes in management practices. Gasteen and Bell (1978) determined that the addition of 80kg/ha of nitrogen and 100kg/ha of phosphorus significantly improved dry matter yields of Rhodes and American

Buffel grasses on overburden materials at Callide mine. Orr (1993) documented cover crop improvements for fertiliser application rates of up to 300kg/ha of nitrogen and 200kg/ha of phosphorus on spoil and soil materials at Curragh. Bell *et al.* (1991) concluded that 400kg/ha of nitrogen and 100kg/ha of phosphorus significantly improved the growth of pasture species on spoil and soil materials tested at Saraji.

The addition of potassium and some other micronutrients have also been shown to improve the growth of pasture species on some spoils in central Queensland, however, the results are highly variable (Bell *et al.* 1991).

5.2.4.2 Symbiotic associations

Pasture legumes are frequently sown with the seed mix at establishment to improve pasture productivity and quality, and commonly occur within the sward (Section 3.3, 3.4). Rates of N fixation across rehabilitation pastures have not been investigated, however, are likely to be dependent on prevailing moisture conditions and P-availability. Silcock *et al.* (1990) suggested that fixation rates by legumes in native Queensland pastures of 1 kgN/ha/year would be high. More recently, Armstrong *et al.* (1999) reported N fixation rates of 11-64 kgN/ha/year for Siratro growing in experimental plots on a cracking clay soil in central Queensland, providing some indication of the potential range achievable. Consideration needs to be given to the persistence of legume species under the influence of grazing. In addition to N-fixing rhizobia, mycorrhizal infection of buffel grass has been observed. Data from Spain (1999 unpublished) indicated a significant linear response of buffel grass growth to VAM infection when grown in mine soils from three different mines.

5.2.5 pH

While many spoils are strongly to extremely alkaline, the available site data suggest that pH has little impact on pasture dry matter (Figure 20). The fitted curve only weakly related dry matter with surface pH, despite limiting the analysis to sites with lower salinity. Nevertheless, the fitted curve took the expected form, showing reduced performance at highly alkaline sites, presumably due to nutrient availability problems. Dry matter also appeared to decline with increasing acidity but site data at lower pH were too restricted to be confident. The data are, however, in agreement with Bell *et al.* (1991) who suggested that pH 5.5 – 8.5 should not be limiting to the growth of pasture species. Best growth appears to be achieved at near-neutral pH, with around a 50 % reduction occurring at the recorded extremes.

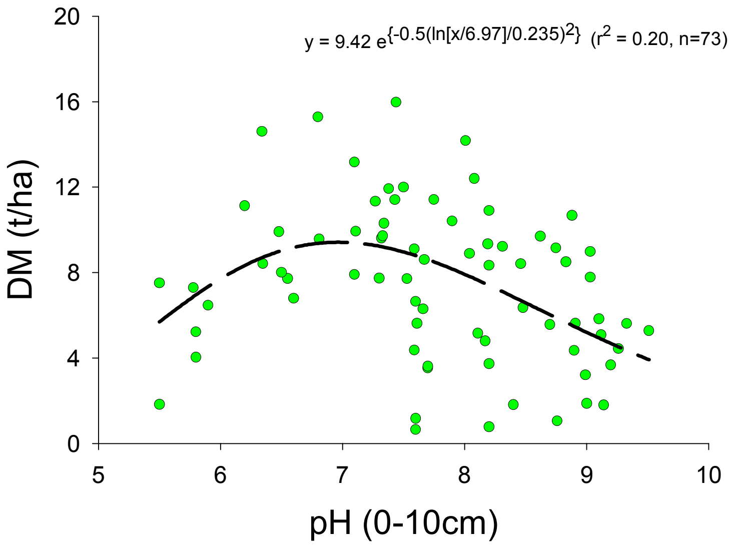

Figure 20. Effect of surface (0-40 cm) pH on pasture dry matter. Data are limited to sites with rootzone salinity < 0.4 dS/m.

5.3 Pasture recovery following fire

Results from an experimental burn at Goonyella (Appendix I) indicate that, under relatively ideal rainfall conditions, recovery in standing cover can be relatively rapid. Pre-burn cover levels or better were attained within six months after the fire, although observations on unmined pastures suggest that the period for recovery may be much longer. New growth is predominantly from existing tussock bases and new tillers rather than recruitment from seed.

Response is in part due to the release of nutrients immobilised within standing and detached litter, which can be substantial in ungrazed rehabilitation pastures (Section 3.5). Preliminary results from the experimental burn at Goonyella indicated that there were no significant losses to the atmosphere of P and major cations. However, long-term pasture recovery would be dependent on the soils capacity to retain nutrients against leaching (its cation exchange capacity), the absence of major erosion events immediately following the burn, and the ability of the system to fix N to balance potentially significant losses of this element due to volatilisation during fire.

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7.0 REFERENCES AND SOURCES OF DATA

7.1 References cited in the text

Armstrong, R.D., McCosker, K., Johnson, S.B., Walsh, K.B., Millar, G., Kuskopf, B., Standley, J. and Probert, M.E. (1999). Legume and opportunity cropping systems in central Queensland. 1. Legume growth, nitrogen fixation, and water use. *Australian Journal of Agricultural Research* **50**, 909-924.

Bell, L.C. (1984). Mining rehabilitation. In. *The Brigalow Belt of Australia.* (Ed A. Bailey) pp. 111-117. Proceedings of a Symposium by the Royal Society of Queensland, Brisbane, 1982. (QDPI: Brisbane.)

Bell, L.C. (1996). Rehabilitation of disturbed land. In. *Environmental management in the Australian minerals and energy industries. Principles and practices.* (Ed D.R. Mulligan) pp. 227-261. (University of NSW Press: Sydney.)

Bell, L.C., Mulligan, D.R. and Mitchell, R.J. (1991). Definition of rehabilitation strategies for pre-strip Tertiary overburden spoil at the Saraji open-cut coal mine. Progress Report No 2 to BHP-Utah Coal Limited. Department of Agriculture, University of Queensland.

Bellairs, S. (1999). Determining ecological indicators for native vegetation and wildlife habitat rehabilitation success at the Blair Athol and Tarong mines. In *Proceedings of the Workshop on Indicators of Ecosystem Rehabilitation Success.* Melbourne, 23-24 October 1998. (Eds. C.J. Asher and L.C. Bell) pp. 105-118. Australian Centre for Mining Environmental Research: Brisbane.

Carroll, C., Merton, L. and Berger, P. (2000). Impact of vegetative cover and slope on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines. *Australian Journal of Soil Research* **38**, 313-327.

Carroll, C. and Tucker, A. (2000). Effects of pasture cover on soil erosion and water quality on central Queensland coal mine rehabilitation. *Tropical Grasslands* **34**, 254-262.

Coaldrake, J.E. and Russell, M.J. (1978). Rehabilitation with pasture after open-cut mining at three sites in the Bowen Coal Basin of Queensland. *Reclamation Review* **1**, 1-8.

Costin, A.B. (1980). Runoff and soil and nutrient losses from an improved pasture at Ginninderra, Southern Tablelands, New South Wales. *Australian Journal of Agricultural Research* **31**, 533-546.

Dalzell, S.A., Stewart, J.L., Tolera, A. and McNeill, D.M. (1995). Chemical composition of *Leucaena* and implications for forage quality. In. *Leucaena - opportunities and limitations.* Proceedings of a workshop held in Bogor, Indonesia 24-29 January 1994 (eds. H.M. Shelton, C.M. Piggin and J.L. Brewbaker), pp. 227-246. ACIAR Proceedings No. 57.

Davies, B. and Willcocks, J. (1992). Climate variability in the Fitzroy catchment. In Fitzroy Catchment Symposium (eds. L.J. Duivenvoorden, D.F. Yule, L.E. Fairweather and A.G. Lawrie), 12 November 1992, University of Central Queensland, Rockhampton.

DME (1995). *Technical guidelines for the environmental management of exploration and mining in Queensland.* Department of Minerals and Energy, Brisbane.

Doll, E.C. and Wollenhaupt, N.C. (1985). Use of soil parameters in the evaluation of reclamation success in North Dakota. In. *Proceedings of the 2nd Annual Meeting, American Society for Surface Mining and Reclamation*, Denver, Colorado, pp. 91-94. American Society for Surface Mining and Reclamation.

Dyson, J.R., Dight, D.C.G., Reynolds, K.C., Elliott, G.L. and Hill, M.J. (1987). Coal mine rehabilitation. End of grant report No. 719. NSW Coal Association. (National Energy Research, Development and Demonstration Program: Canberra).

Eastment, H.T., Russell, M.J. and Toleman, M.A. (1989). Spatial variability in spoil sampling. *Landscape and Urban Planning* **17**, 121-126.

Elliott, G.L. and Reynolds, K.C. (2000). Soils and extractive industries. In. Soils. Their properties and management. (Eds P.E.V. Charman and B.W. Murphy) (Oxford University Press:Melbourne.)

Elliot, P., Gardner, J., Allen, D. and Butcher, G. (1996). Completion criteria for Alcoa of Australia Limited's bauxite mine rehabilitation. In *Proceedings of the 3rd International and 21st Annual Minerals Council of Australia Environmental Workshop*, Newcastle, 14–18 October, 1996, Vol. 2, pp. 79–89. Minerals Council of Australia: Canberra.

Fitzpatrick, R.W., Hollingsworth, I.D. and Soole, P.K. (1995). Soil description, classification and mapping. In. *Measurement of the rate of soil formation in spoil and rehabilitated spoil landforms at BHP Australia Coal Pty Ltd mines, central Queensland* (A.V. Spain *et al*.). Report to BHP Australia Coal Pty Ltd, January 1995. Project MRX0029 – 'Soil from spoil'. CSIRO Minesite rehabilitation research program.

Gasteen, W.F. and Bell, L.C. (1978). Spoilpile reclamation trials at Callide Coal Mine of Thiess Bros. In. *Proceedings of The Australian Institute of Mining & Metallurgy Conference*, North Queensland, September 1978. pp. 385-394.

Graham, T.W.G., Myers, R.J.K., Doran, J.W., Catchpoole, V.R. and Robbins, G.B. (1985). Pasture renovation: the effect of cultivation on the productivity and nitrogen cycling of a buffel grass (*Cenchrus ciliaris*) pasture. In Proceedings XV International Grasslands Congress pp. 640-642.

Grigg, A.H. (1999a). Monitoring of rehabilitated and unmined sites at the Goonyella Riverside mine. Assessment of vegetation, soils and erosion, October 1998. Report to BHP Goonyella Riverside mine, May 1999. Centre for Mined Land Rehabilitation, University of Queensland.

Grigg, A.H. (1999b). Rehabilitation monitoring at the Gregory mine 1998. Assessment of vegetation, soils and erosion, December 1998. Report to BHP Gregory mine, August 1999. Centre for Mined Land Rehabilitation, University of Queensland.

Grigg, A.H. (2000). Rehabilitation monitoring at the Goonyella Riverside mine 1999. Assessment of vegetation, soils and erosion, September 1999. Report to Goonyella Riverside mine, BHP Coal Pty Limited, February 2000. Centre for Mined Land Rehabilitation, The University of Queensland.

Hannan, J.C. (1995). Mine rehabilitation. A handbook for the coal mining industry. 2nd edition. (NSW Coal Association: Sydney).

Hannan, J.C. and Gordon, R.M. (1996). Environmental management of coal mines in the Hunter Valley, New South Wales. In '*Environmental management in the Australian minerals and energy industries. Principles and Practices*' (Ed. D.R. Mulligan), pp. 265-290. Australian Minerals and Energy Environment Foundation. (University of New South Wales Press: Sydney).

Harwood, M.R. (1998). The selection of new pasture grasses for the revegetation of open-cut coal mines in central Queensland. PhD Thesis, Centre for Mined Land Rehabilitation, University of Queensland.

Harwood, M.R., Hacker, J.B. and Mott, J.J. (1999). Field evaluation of seven grasses for use in the revegetation of lands disturbed by coal mining in Central Queensland. *Australian Journal of Experimental Agriculture* **39**, 307-316.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E. and Schulze, E.D. (1996). A global analysis of root distributions for terrestrial biomes. *Oecologia* **108**, 389-411.

Kelly, R.E. (1979). A description of natural environment features of the Isaac River catchment and of the coal-strip mining operations. In *Management of lands affected by mining.* (Eds R.A. Rummery and K.M.W. Howes) pp. 33-54. (CSIRO: Melbourne.)

Lang, R.D. (1979). The effect of ground cover on surface runoff from experimental plots. *Journal of the Soil Conservation Service of N.S.W.* **35**, 108-114.

Lang, R.D. and McCaffrey, L.A.H. (1984). Ground cover – its effects on soil loss from grazed runoff plots, Gunnedah. *Journal of the Soil Conservation Service of N.S.W.* **40**, 56-61.

Leggate, J., Emmerton, B. and Kratzing, D. (1990). *Guidelines for rehabilitation of central Queensland coal mines.* Queensland Department of Resource Industries, Brisbane.

Loch, R.J. (1997). Landform design – better outcomes and reduced costs by applying science to above- and below-ground issues. Proceedings 22nd Annual Minerals Council of Australia Environmental Workshop, Adelaide, October 1997. pp. 550-563.

Loch, R. J. (2000a). Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong, Queensland. *Australian Journal of Soil Research* **38**, 299-312.

Loch, R. J. (2000b). Using rainfall simulation to guide planning and management of rehabilitated areas: Part I. Experimental methods and results from a study at the NorthParkes mine, Australia. *Land Degradation and Development* **11**, 221-240.

Loch, R.J. and Orange, D.N. (1997). Changes in some properties of topsoil at Tarong coal Meandu mine coalmine with time since rehabilitation. *Australian Journal of Soil Research* **35**, 777-784.

Loch, R. J. and Pocknee, C. (1998). Field rainfall simulation. In Post Mining Landscape Parameters for Erosion and Water Quality Control. Report to ACARP, Projects C1629 and C4011. The University of Queensland, pp. 55-78.

McCallum, N.J. and Grigg, A.H. (1999). Native tree establishment trial at the Blackwater open-cut coal mine. Report to BHP Blackwater mine, November 1999. Centre for Mined Land Rehabilitation, University of Queensland.

McIvor, J.G. and Gardener, C.J. (1985). Germination of introduced pasture species in the semi-arid tropics. In *Ecology and Management of the World's Savannas.* (Eds. J.C. Tothill and J.J. Mott) pp.277-279. (Australian Academy of Science: Canberra).

McIvor, J.G., Williams, J. and Gardener, C.J. (1995). Pasture management influences runoff and soil movement in the semi-arid tropics. *Australian Journal of Experimental Agriculture* **35**, 55-65.

McLennan, T.P.T. (1994). Review of research investigations and existing data on the characteristics of coal mining spoil, Bowen Basin, central Queensland. CSIRO Report to BHP Australia Coal Project MRX0029 – 'Soil from spoil', February 1994.

Minson, D.J. (1990). *Forage in ruminant nutrition.* (Academic Press:Sydney.)

Orr, M. S. (1993). Strategies for native species establishment at the Curragh open-cut coal mine, central Queensland. Master of Agricultural Science. Department of Agriculture, The University of Queensland.

Robbins, G.B., Bushell, J.J. and McKeon, G.M. (1989). Nitrogen immobilisation in decomposing litter contributes to productivity decline in ageing pastures of green panic (*Panicum maximum* var. *trichoglume*). *Journal of Agricultural Science, Cambridge* **113**, 401-406.

Robertson, F.A., Myers, R.J.K. and Saffigna, P.G. (1993). Distribution of carbon and nitrogen in a long-term cropping system and permanent pasture system. *Australian Journal of Agricultural Research* **44**, 1323-36.

Robertson, F.A., Myers, R.J.K. and Saffigna, P.G. (1995). Effects of modifying plant carbon inputs on nitrogen distribution in intact cores of a perennial grass pasture. *Australian Journal of Soil Research* **33**, 297-310.

Roe, P.A., Mulligan, D.R. and Bell, L.C. (1996). Environmental management of coal mines in the Bowen Basin, central Queensland. In *Environmental management in the Australian minerals and energy industries. Principles and practices.* (Ed D.R. Mulligan) pp. 290-315. (University of NSW Press: Sydney.)

Rosenthal, K.M. and Hammer, G.L. (1979). Heatwave and maximum temperature probabilities. *Queensland Agricultural Journal* **105**, 72-93.

Russell, M.J. (1974). *Annual Report 1974 – Bowen Basin Spoil Heap Revegetation*. Report to Utah Development Company.

Russell, M.J. (1975). *Annual Report 1975 – Bowen Basin Spoil Heap Revegetation*. Report to Utah Development Company.

Russell, M.J. (1979). Spoil-heap revegetation at Open-cut Coal Mines in the Bowen Basin of Queensland, Australia. In. *Ecology and Coal Resource Development* (Pergamon Press:New York.)

SCA (1990). *Feeding standards for Australian livestock. Ruminants.* Standing Committee on Agriculture, Ruminants Subcommittee. (CSIRO: Melbourne.)

SalCon (1997). Salinity Management Handbook. Queensland Department of Natural Resources, Brisbane.

Scanlan, J.C. and McIvor, J.G. (1993). Pasture composition influences soil erosion in *Eucalyptus* woodlands of northern Queensland. In Proceedings 17th International Grassland Congress. pp. 65-66.

Shaw, R.J. (1995). A unified soil property and sodicity model of salt leaching and water movement. PhD thesis, Department of Agriculture, University of Queensland.

Sheridan, G.J., So, H.B., Loch, R.J. and Walker, C.M. (2000a). Estimation of erosion model erodibility parameters from media properties. *Australian Journal of Soil Research* **38**, 265-284.

Sheridan, G.J., So, H.B., Loch, R.J., Pocknee, C. and Walker, C.M. (2000b). Use of laboratory-scale rill and interill erodibility measurements for the prediction of hillslope-scale erosion on rehabilitated coal mine soils and overburdens. *Australian Journal of Soil Research* **38**, 285-297.

Silburn, D.M., Carroll, C., Ciesolka, C.A.A. and Hairsine, P. (1992). Management effects on runoff and soil loss from native pastures in central Queensland. In Seventh Biennial Conference of the Australian Rangeland Society, Cobar. pp.294-295.

Silcock, R. (1991). Pastures, trees and shrubs for rehabilitating mines in Queensland. Impediments to their use on opencut coal and alluvial mines. Australian Minerals and Energy Environment Foundation, Occasional Paper No. 1. QDPI, Brisbane.

Silcock, R.G., Brown, R.F. and McKeon, G.M. (1990). Effects of plant morphology and physiology on native pasture management. In 'Native pastures in Queensland. The resources and their management'. (Eds W.H. Burrows, J.C. Scanlan and M.T. Rutherford) pp. 34-51. QDPI: Brisbane.

Spain, A.V. (1999). Outcomes of recent research: post-mining land use. Unpublished workshop papers, in 'Rehabilitation issues for the coal industry in Queensland, Emerald, 19-20 July 1999'. Australian Centre for Mining Environmental Research, Brisbane.

So, H.B., Sheridan, G.J., Loch, R.J., Carroll, C., Willgoose, G., Short, M. and Grabski, A. (1998). Post mining landscape parameters for erosion and water quality control. Final Report to ACARP, November 1998. 147 pp.

Ward, S.C. (1999). Assessing rehabilitation development on Alcoa's bauxite mines. In *Proceedings of the Workshop on Indicators of Ecosystem Rehabilitation Success.* Melbourne, 23-24 October 1998. (Eds. C.J. Asher and L.C. Bell) pp. 91-103. Australian Centre for Mining Environmental Research: Brisbane.

Willcocks, J. (1993). Climate. In. *Farming Systems for Downs and Brigalow Soils in Central Queensland.* Proceedings of a workshop held at Emerald Pastoral College, 16-18 September, 1991 (Eds A.L. Garside, B.J. Radford and A.J. Carr.) (Department of Primary Industries: Brisbane.)

Willcocks, J. and Filet, P. (1993). Assessing the productivity of pastures in the Central Highlands region of Queensland, Australia. In 'Proceedings of the XVII International Grassland Congress, Australia/New Zealand, February 1993' Vol. I, 367-368. (Dunmore Press: New Zealand.)

7.2 Other sources of data

Bowen, D., Grabski, A., Taylor, P., Teague, A., Appleton, D. and Mulligan, D. (1997). Monitoring of rehabilitation at the Blackwater mine. An assessment of soils, vegetation and erosion. Report to Blackwater mine, BHP Coal Pty Limited, December 1997. Centre for Mined Land Rehabilitation, The University of Queensland.

Bowen, D., Grabski, A., Stanford, M., Teague, A., Appleton, D., Taylor, P. and Mulligan, D. (1998). Monitoring of rehabilitation at the Moura mine. An assessment of soils, vegetation and erosion. Report to Moura mine, BHP Coal Pty Limited, February 1998. Centre for Mined Land Rehabilitation, The University of Queensland.

Catchpoole, S. and Grigg, A.H. (2000). Rehabilitation monitoring at the Gregory mine 1999. Assessment of vegetation, soils and erosion, December 1999. Report to BHP Gregory mine, June 2000. Centre for Mined Land Rehabilitation, The University of Queensland.

Elsol, J. (1997a). Gregory mine vegetation monitoring. Baseline 1996. Report to BHP Gregory mine by Land Reclamation Services, January 1997.

Elsol, J. (1997b). Norwich Park mine – 1996 vegetation monitoring report. Land Reclamation Services.

Emmerton, B.R. (1995). Monitoring of rehabilitated soil/spoil profiles, Goonyella/Riverside mine (Initial monitoring). Report to BHP Goonyella Riverside mine by Land Reclamation Services, September 1995.

Emmerton, B.R. (1996). Monitoring of rehabilitated soil/spoil profiles, Goonyella/Riverside mine (Second monitoring). Report to BHP Goonyella Riverside mine by Land Reclamation Services, October 1996.

Emmerton, B. (1997). Monitoring of rehabilitated soil/spoil profiles, Gregory mine (Initial monitoring, November 1996). Report to BHP Gregory mine by Land Reclamation Services, April 1997.

Emmerton, B.R. (1998a). Monitoring of rehabilitated soil/spoil profiles, Goonyella/Riverside mine (Third monitoring). Report to BHP Goonyella Riverside mine by Land Reclamation Services, February 1998.

Emmerton, B.R. (1998b). Monitoring of rehabilitated soil/spoil profiles, Norwich Park mine (Third monitoring). Report to BHP Norwich Park mine by Land Reclamation Services, June 1998.

Fletcher, G. (1995). Goonyella Riverside mine Erosion Baseline Study 1995. Report to BHP Goonyella Riverside mine by Land Reclamation Services, July 1995.

Fletcher, G. (1996). Goonyella Riverside mine Erosion Monitoring 1996. Report to BHP Goonyella Riverside mine by Land Reclamation Services, October 1996.

Fletcher, G. (1997a). Norwich Park mine Erosion Monitoring 1996. Report to BHP Norwich Park mine by Land Reclamation Services, April 1997.

Fletcher, G. (1997b). Goonyella Riverside mine Erosion Monitoring 1997. Report to BHP Goonyella Riverside mine by Land Reclamation Services, October 1997.

Fletcher, G. (1997c). Gregory mine erosion monitoring 1996. Report to BHP Gregory mine by Land Reclamation Services, November 1997.

Grigg, A.H. and Catchpoole, S. (1999). Rehabilitation of pre-strip Tertiary spoils at Saraji mine. Assessment of soil and vegetation development 8 years after establishment, June 1999. Report to BHP Saraji mine, December 1999. Centre for Mined Land Rehabilitation, University of Queensland.

Moore, G. (1982). Grass cover on regenerated spoilpiles. Blackwater mine internal report. Utah Development Company, May 1982.

Murray, G.C., Grundy, M.J., Bell, L.C., Whiteman, P.C. (1983). Rehabilitation strategies at the Collinsville Open-cut Coal Mine. In *Northern Australian Mine Rehabilitation Workshop, Collinsville.* pp.13-22.

Winters, S. (2000). Annual pasture monitoring. Internal report. BHP Peak Downs mine. (Collation of transect monitoring data 1977-2000).

APPENDIX I

GOONYELLA CATCHMENT FIRE STUDY
(Collaboration with ACARP Project C7006)

Background

Fire is generally excluded from rehabilitated grasslands in the Bowen Basin, except for sporadic accidental ignitions and incursions from surrounding properties. Exclusion is considered necessary to protect the vegetation communities in the early stages of their development, but exclusion in more mature systems is arguably a response to perceived risks of erosion if cover is removed. However, the infrequent fire regime, combined with an absence of cattle grazing in these systems, can often result in large accumulations of above-ground dry matter (up to 20 t/ha). The associated nutrient pools may be substantial.

Fire is a major pathway for nutrient recycling in northern Australian savannas (Holt and Coventry 1990), but there are risks of permanent loss of nutrients, either through direct transfers to the atmosphere or indirectly in eroded ash and sediment during storms. Research suggests that under frequent fire regimes, significant losses of N may occur *if there is insufficient biological fixation* (Cook 1994), particularly in environments with low edaphic nutrient capital.

With the cessation of mining, a more frequent burning regime in rehabilitated areas is almost certain to occur, as management of these areas become integrated with adjacent pastoral land. There is therefore the possibility that the rehabilitated systems will degrade, as fire removes the initial accumulated above-ground nutrient pool and subsequently causes small but persistent losses of nutrients over time. Rehabilitated systems are generally poor in total N, and have relatively steep terrain, and are thus especially prone to disturbances which remove cover in the short term and may degrade over the longer term if exogenous inputs of nutrients are exceeded.

The effects of fire on these rehabilitated systems needs to be understood in order to define post-mining land use options and associated guidelines for assessing the success of rehabilitation efforts in achieving those land-use objectives.

Aims

There are two main risks associated with the occurrence of fire in rehabilitated grasslands. There is the short-term impact on the vegetative surface cover which provides protection against erosion from raindrop impact and overland flow. In the longer-term, there is the potential for nutrient depletion, with a resultant reduction in site productivity and capacity of the system to resist degradation. The main aims of the study were therefore to:

1. Measure the recovery of the community after fire with reference to its erosion protection capabilities, and
2. Quantify the loss of nutrients from the fuel during fire.

Site description and methods

Experimental site

The experiment was conducted on three small (<2 ha) catchments at the southern end of the Goonyella Riverside mine, on spoil heaps created from a dam excavation (Figure 1). The catchments were originally constructed in January 1993 to monitor minesite erosion at the catchment scale under ACARP Project C7006 ‘Sustainability indicators for coal mine rehabilitation’ and were fully instrumented to measure rainfall, runoff and soil loss.

Burns

The site encompasses three catchments (Figure 1), for the purposes of this study comprising a Control which remained unburnt (Catchment A), and two treatment catchments (Catchments B and C) which were burnt initially on 17 December 1999. A second burn on Catchment C only was subsequently undertaken the following year on 16 October 2000.

In the first fire, near-complete burns were achieved across both catchments. Where cover was originally continuous, complete removal occurred, but fire did not carry where tussocks became patchy (Plates 1, 3, 4 and 5). Cover removal of 85% and 90% were estimated for Catchments B and C, respectively. The second fire on Catchment C in October 2000 carried poorly due to insufficient fuel despite impressive dry matter gain since the initial burn.

Rainfall conditions following the initial burn were ideal for pasture recovery, with approximately 50mm falling within 24 hours of the burn and 100mm in the first month. A total of eight falls were recorded in the three months post-burn. Rainfall after April 2000 generally decreased below average levels, with the 2000-2001 season also drier than average. More detailed rainfall data are provided in the C7006 report.

Data collection

A pre-burn assessment was undertaken on 30 November 1999, with post-burn assessments made on 24 December 1999, 23 June 2000, 3 October 2000 and 13 March 2001 (Catchments A and B only). Additional measures were carried out by C7006 project members one and 2.5 months post-burn.

Projected cover and either standing yield (CMLR, using the BOTONAL method) or total above-ground dry matter (C7006 by quadrat harvests) were recorded at each survey in 2000. Standing yield excludes detached fallen litter and so underestimates total dry matter, but in burnt catchments over the monitoring period, there was very little litter and the two measures were essentially comparable. In June and October 2000 and March 2001, ground contact cover elements were also assessed by recording cover categories (bare ground or rock, grass tussock, collapsed or detached litter including seed), using a point frequency frame. This comprised ten vertical rods held within a horizontal rod 1m in length. Between 15 and 36 of these measures were taken in each catchment.

Efforts were made in the second burn to measure nutrient losses as a result of combustion and particulate removal via updraught (but not removal in overland flow or leaching). A total of 20 circular quadrats (radius 0.5m) were located on a systematic grid within Catchment C and placed such that approximately equal quantities of biomass resided in each half. Prior to the burn, all above-ground material was removed from half of each quadrat for weighing and nutrient analysis. Material in the other half was left undisturbed. Three circular tins (diameter 75mm) were placed on the ground within the undisturbed material of each quadrat with lids removed to collect ash and fragments of charred vegetation. Fallen litter was minimal within these areas and was ignored. Following the burn, tins were removed and any partially burnt residue material collected separately. Dry matter losses were thus calculated as the difference between pre-burn biomass and post-burn weights of ash and remaining standing material.

Partially burnt materials were dried, weighed and ground to < 2mm for nutrient analysis. Ash was dried and weighed, then bulked to give a single sample per quadrat. Pre-burn and post-burn standing residue samples were analysed for nutrients by digestion in nitric-perchloric 5:1 acid, followed by ICPAES analysis. Ash samples were analysed for nutrients by sonicating in 25ml of warm 10% HCl for 10 minutes, followed by ICPAES analysis. Total C and N were determined on all samples by combustion using a LECO CNS-2000.

Transfer of nutrients to the atmosphere was calculated as the difference in nutrient capital between pre-burn dry matter and post-burn residue plus ash.

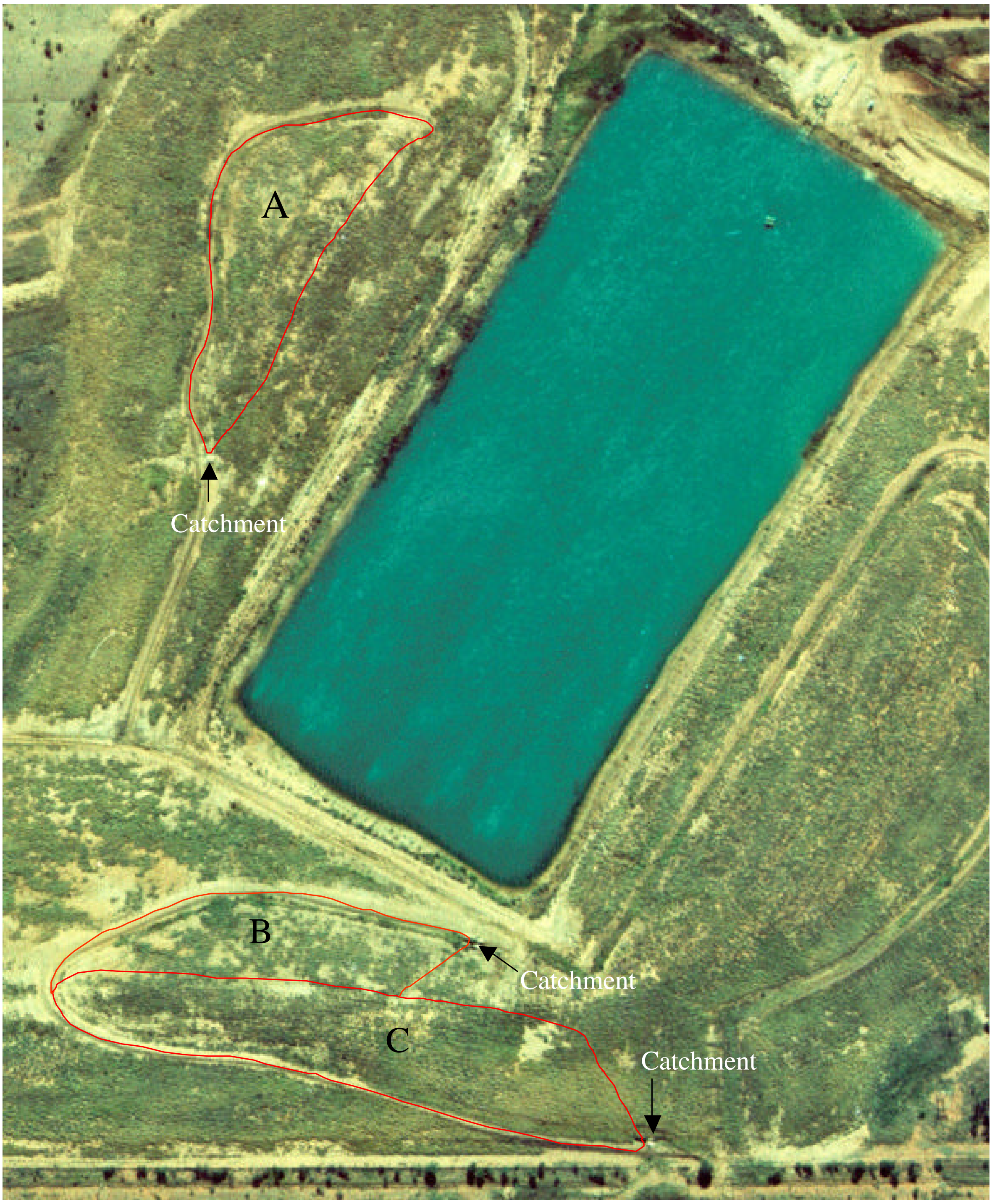

Figure 1. Overview of the experimental catchments at Goonyella Riverside mine, prior to experimental burns in Catchments B and C.

Results

Pasture recovery

Prior to the burn, all catchments supported a pasture dominated by buffel grass, with standing yields of up to around 9 t/ha. Mean cover levels were high (>75%) across all catchments although this was patchiest on Catchment B (Figure 1) and caution is required in cross-catchment comparisons after fire.

Recovery in standing cover was rapid, with up to 50% cover after just one month and reaching levels comparable to the pre-burn state or better six months after the fire (Figure 2, Plates 1 and 2). Almost all of this cover was contributed by buffel grass. New growth was predominantly from existing tussock bases and new tillers (Plate 6), with little apparent recruitment from seed despite prolific seed production by February-March 2000, three months after the fire. Standing yields followed a similar pattern to cover, reaching pre-burn levels within the same time frame (Figure 3).

However, while projected cover and standing dry matter had recovered in the burnt catchments after six months, the soil surface remained relatively unprotected (Figure 4). In the unburnt control, a significant proportion of the cover elements in contact with the ground was contributed by detached or collapsed litter. In the burnt catchments, detached or collapsed litter contributed 30-50%, leaving a large proportion of bare ground. Observations made in the first few months after the fire indicated that much of this cover was formed by thin layers of accumulated buffel grass seed, rather than thick mats of stem and leaf blade material that were evident in the unburnt control. Measured total litter cover in the burnt catchments did not appear to alter greatly within the 15 months after the first burn.

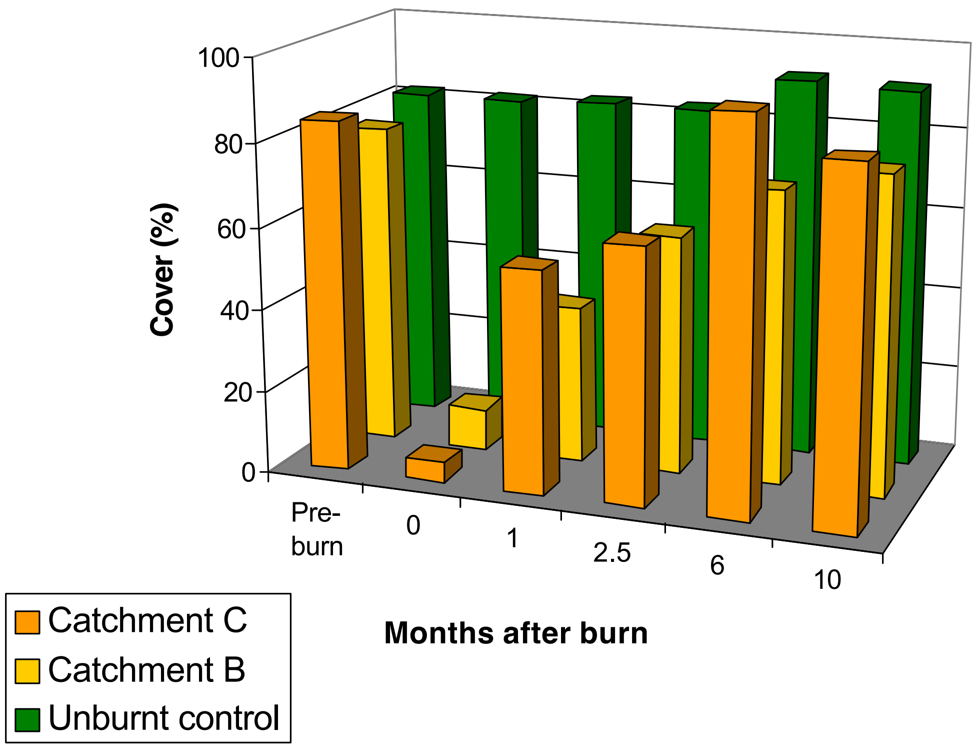

Figure 2. Changes in projected cover within burnt and unburnt control catchments immediately prior to and following an experimental burn in December 1999.

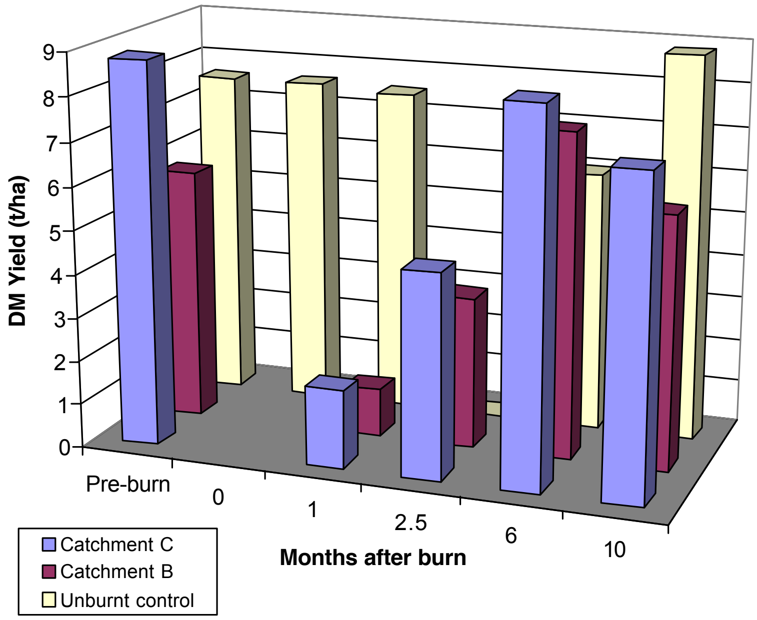

Figure 3. Changes in standing dry matter yield within burnt and unburnt control catchments immediately prior to and following an experimental burn in December 1999.

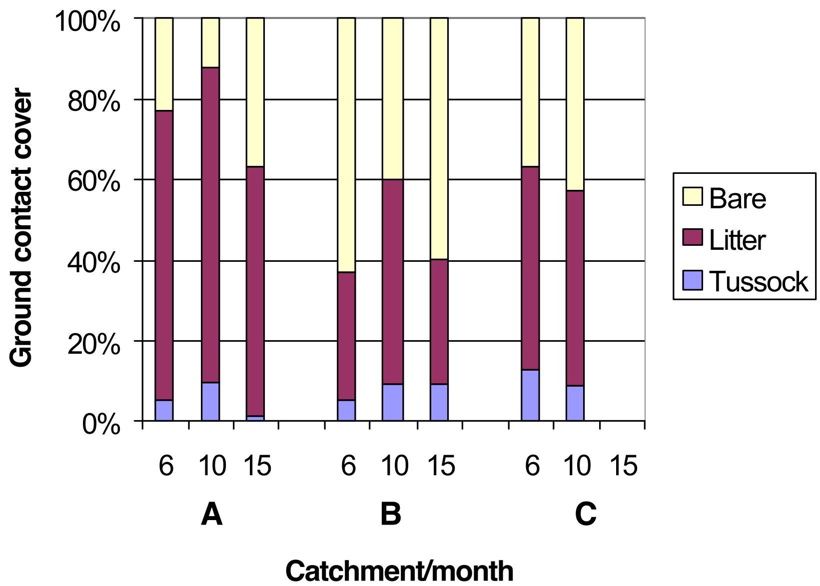

Figure 4. Ground contact cover elements and bare ground in burnt catchments (B and C) and an unburnt control (A) at 6, 10 and 15 months post-burn.

Runoff and sediment concentrations

Detailed data on runoff and sediment concentrations are provided in the final report of ACARP Project C7006. The following results are provided here to illustrate trends consistent with observed recovery in vegetation. Sediment concentrations of runoff in the burnt catchments increased to >3 g/L immediately following the burn, and then dropped as the pasture recovered (Figure 5). Sediment movement in the unburnt control remained low.

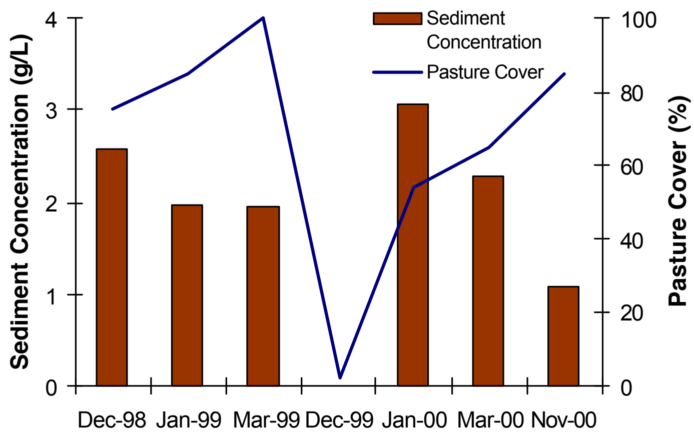

Figure 5. Changes in sediment movement in relation to standing cover, Catchment C.

Runoff volumes on burnt catchments also increased after the burn, but in contrast to the pattern observed in sediment concentrations, these remained significantly higher than the unburnt control catchment up to a year after the burn (Figure 6). Total soil movement from the burnt catchments remained relatively constant, despite the decline in sediment concentrations.

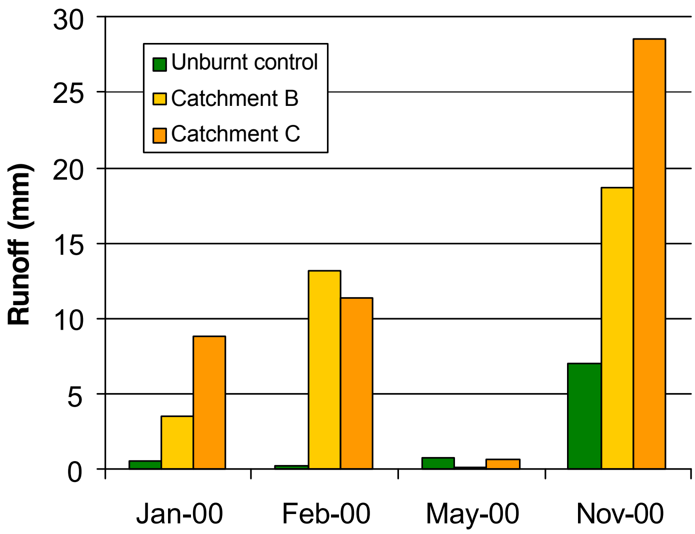

Figure 6. Runoff from each catchment after the burn.

Nutrient losses

Fire spread was poor during the second burn, and data were obtained from only five of the 20 quadrats established. Accidental ignition of pasture-based rehabilitation adjacent to Catchment C which caused more complete cover removal suggested that sward structure rather than weather conditions were at least partly responsible for the poor result. Of the five available quadrats, the assumption of equal dry matter in each quadrat half was obviously invalid for one of these, and data were ignored. Due to the small number of usable quadrats, therefore, the results should be viewed as indicative only.

Estimates of pre-burn dry matter levels in the burnt quadrats were lower than for the total catchment (Table 1 cf. Figure 3), however, nutrient contents were comparable to pasture grab sample data from elsewhere on the mine (Grigg 1999). Concentrations of all nutrients except N and to a lesser extent S were greater in ash compared to the pre-burn material, while there appeared to be a decrease in cation content in the unburnt standing residue. There were apparent increases in Ca capital following the burn in each quadrat, which indicated that the assumption of equal dry matter loads in each half of the quadrat was weak and/or appreciable quantities of ash entered the quadrats during the fire. Post-burn ash weights (Table 1) were therefore corrected, maintaining the assumption of equal dry matter loads in each quadrat half and further assuming for the purposes of this analysis no loss of Ca via entrained particulates. While unlikely to be strictly held, the assumptions were considered adequate given the level of data available. A consequence of this approach was that no differentiation could be made between losses by volatilisation or as entrained particulate matter.

Table 1. Mean mass of material and nutrient concentrations in pre- and post-burn components.

Component	Mass* (kg/ha)	N (%)	P (%)	S (%)	Ca (%)	K (%)	Mg (%)
Pre-burn pasture	2570 ± 580	0.82	0.18	0.14	0.32	1.27	0.14
Standing residue	780 ± 240	0.83	0.25	0.15	0.07	1.07	0.09
Ash	250 ± 30	0.56	0.68	0.19	3.20	3.28	0.82

* Values are mean ± SE (n=4).

The transfers of plant nutrients and mass to the atmosphere during the fire are presented in Table 2 as both absolute amounts and as a proportion. Mean combustion of 60% is less than recorded for tropical savannas (Cook 1994) and consistent with a poorer experimental burn. Losses of the relatively volatile N and S were > 50%, however transfer of other elements was lower. Apparent small gains in P are indicative of the errors inherent in these data but the result is suggestive of minimal losses of this element overall. Losses of S and K were positively and significantly correlated with fuel load (Figure 7). Similarly, transfer of N was positively related to fuel load (Figure 7) although the relationship was non-significant.

Table 2. Transfer of plant mass and associated nutrients to the atmosphere during the experimental burn. Data are presented on the basis of no loss of Ca (refer text). A negative value indicates net import.

	Mass	N	P	S	K	Mg
Total (kg/ha)	1540	13.7	0.44	1.94	13.93	0.72
Percentage	60	62	-5	52	44	18

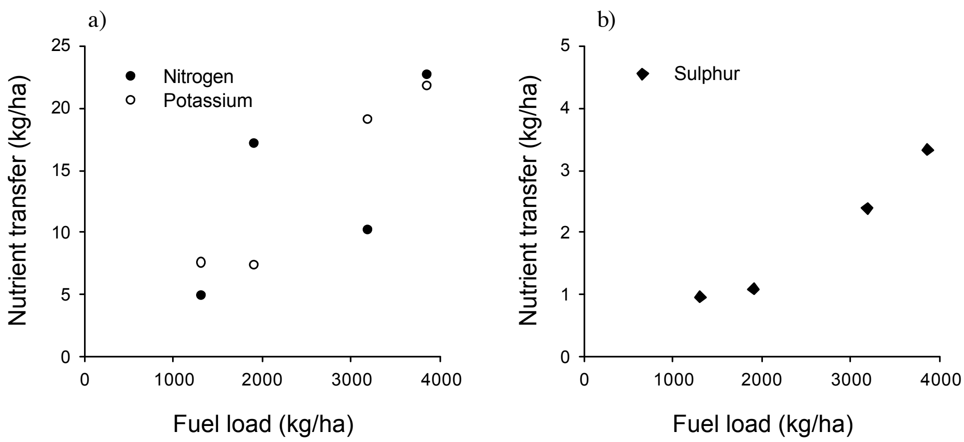

Figure 7. Relationship between fuel load and the transfer of a) N and K, and b) S to the atmosphere during an experimental burn.

Discussion

Pasture recovery and erosion risk

The study has shown that while the pasture gives a visual impression of recovering well after fire, the period of potential risk of surface soil movement is likely to be much longer. The vigorous return of an overhead cover in this study was assisted by favourable rainfall patterns following the burn, but the growth belies the lack of cover at the ground surface, which in the unburnt state is derived largely from detached and collapsed litter. Such a litter layer would be expected to redevelop in burnt areas with time, but in these tussock grasslands with root contact of 10% or less (Figure 4 and plates), the litter component must play a critical role in maintaining surface stability.

Soil loss occurs as a result of both detachment and subsequent entrainment in overland flow. The recovery in grass crowns will act to reduce raindrop impact, reflected in the decrease in sediment concentration with time (Figure 5), but the absence of effective detached litter constituting 'large' cover elements (Loch 1997) permits potentially high rates of erosion to occur.

McIvor *et al*. (1995) suggest that soil loss is controlled by the capacity of a pasture to supply sediment, rather than the capacity of runoff waters to transport that sediment. The results indicate that sediment concentrations decrease in line with increases in overhead cover, consistent with a reduction in sediment detachment caused by raindrop impact. The runoff results, however, indicate that there are insufficient impediments to overland flow in the burnt catchment, and total runoff is much greater. McIvor *et al*. (1995) found that on tussock rangelands with low slope - conditions parallel with the current study site - velocity and depth of runoff do not increase consistently with increasing slope length. They concluded that maintenance of surface 'roughness', which includes detached and collapsed litter, is important in managing surface stability. The presence of a rough furrowed surface in the catchment (Plate 3) would also be important (Carroll *et al*. 2000), but these features could not be relied upon in the longer term, particularly where cattle re-introduction may accelerate 'smoothing' of the soil surface.

Re-instatement of an effective litter layer had not been achieved within the 15 month study period. Some litter cover in the form of thin layers of seed and detached matter was present, but more substantial accumulation would necessitate the collapse of presently standing material. It seems reasonable to suggest that low surface cover may persist for a two year period or more following a burn. Such a period will cover at least one wet season in which high intensity storms may occur, with the pasture at risk of rill initiation and gullying, particularly on steeper or longer slopes.

Nutrient loss

The nutrient loss results emanating from the second experimental burn should be qualified by the small amount of replication obtained and need to be viewed in the context of assumptions made regarding fuel loads in each quadrat half and possible ash additions from outside the quadrats. Further, no distinction could be made between volatile losses and removal as particulates which will be redeposited within the landscape (Cook 1994), thereby potentially overestimating losses of the less volatile elements such as K and Mg. However, the results are reasonably consistent with published data and can be viewed as an initial indication of likely effects on nutrient transfers to the atmosphere in these buffel-dominated rehabilitation pastures.

Relative contributions of volatile in contrast to particulate pathways for nutrient transfer are related to the vaporization temperature of an element and the fire intensity (Raison *et al*. 1985). Relatively higher losses of N and S, and lower losses of P, K and Mg are consistent with known volatilisation of the former at low temperatures and the presumed low intensity of the experimental burn. Transfers of N of 90-96% have been reported for tropical savannas (Norman and Wetselaar 1960, Cook 1994), higher than observed in this study, but combustion percentages in these studies were also higher (83-94%).

Table 3 indicates that losses of nutrients other than N are negligible when compared with quantities in the soil, with an estimated net import of S in rainfall. Since N transfers were positively related to fuel load, which can be substantial in these ungrazed pastures (Figure 3), the potential for significant N losses compared with the available soil pool during fire is high. Information on rates of N fixation in these systems is poor and is an area requiring further work, but will vary with legume content, soil nitrate levels and environmental conditions. The results suggest that an annual burning regime may well rapidly deplete available N reserves. However, the second burn showed that there is insufficient fuel to carry a complete burn every year, a view supported by practices of only opportunistic burns on adjacent pastoral lands, which would mitigate against longer-term degradation.

Table 3. Comparison of nutrient fluxes (kg/ha) in a single fire and estimated input via rainfall with available nutrient capital in the soil. Soil data are from Grigg (1999) for an unburnt site immediately adjacent to the experimental catchments and refer to nutrients in the main rootzone to a depth of 40cm. Soil capital is estimated assuming a bulk density of 1.2 t/m^3.

Parameter	**N**	**P**	**K**	**Mg**	**S**
Rainfall input*	2	0.3	1.1	0.4	3.1
Net transfer	11.7	0.14	12.83	0.32	-1.16
Soil content**	9.6	105	341	1337	530

* Data from Noller *et al.* (1985). ** NO_3-N, Colwell P, exchangeable cations, SO_4-S.

No account has been taken of nutrient loss in overland flow in this study, taking note of the observed increased runoff after fire. Studies have shown that timing of fire in relation to rainfall patterns is critical (e.g. Townsend and Douglas 2000) and this will equally apply in these systems.

Conclusions

The results to date reaffirm the importance of projective cover in reducing the potential for erosion. They also highlight the important role that detached and collapsed litter plays in increasing surface 'roughness' to reduce runoff.

Nutrient losses to the atmosphere during a fire in these pastures are related to fuel loads, with implications for grazing management. While results are indicative only, they do point to the fate of N during fire as being the most important. Further work is required to reliably estimate rates of symbiotic and non-symbiotic N fixation.

References

Carroll, C., Merton, L. and Berger, P. (2000). Impact of vegetative cover and slope on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines. *Australian Journal of Soil Research* **38**, 313-327.

Cook, G.D. (1994). The fate of nutrients during fires in a tropical savanna. *Australian Journal of Ecology* **19**, 359-365.

Grigg, A.H. (1999). Monitoring of rehabilitated and unmined sites at the Goonyella Riverside mine. Assessment of vegetation, soils and erosion, October 1998. Report to BHP Goonyella Riverside mine, May 1999. Centre for Mined Land Rehabilitation, University of Queensland.

Holt, J.A. and Coventry, R.J. (1990). Nutrient cycling in Australian savannas. *Journal of Biogeography* **17**, 427-432.

Loch, R.J. (1997). Landform design – better outcomes and reduced costs by applying science to above- and below-ground issues. Proceedings 22nd Annual Minerals Council of Australia Environmental Workshop, Adelaide, October 1997. pp. 550-563.

Noller, B.N., Currey, N.A., Cusbert, P.J., Tuor, M, Bradley, P. and Harrison, A. (1985). Temporal variability in atmospheric nutrient flux to the Magela and Nourlangie Creek system, Northern Territory. *Proceedings Ecological Society of Australia* **13**, 21-31.

Norman, M.J.T. and Wetselaar, R. (1960). Losses of nitrogen on burning native pasture at Katherine, N.T. *Journal Australian Institute Agricultural Science*, September, 272-273.

Raison, R.J., Khanna, P.K. and Woods, P.V. (1985). Mechanisms of element transfer to the atmosphere during vegetation fires. *Canadian Journal of Forest Research* **15**, 132-140.

Townsend, S.A. and Douglas, M.M. (2000). The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia). *Journal of Hydrology* **229**, 118-137.

Plates

Plate 1. Catchment C from the instrumented outlet one week after the burn on 17.12.99.

Plate 2. Catchment C from the instrumented outlet in June 2000, approximately 6 months after the burn.

Plate 3. Catchment B looking toward the instrumented outlet one week after the burn on 17.12.99.

Plate 4. Catchment B one week after the burn on 17.12.99.

Plate 5. Catchment C one week after the burn on 17.12.99 showing poor fire spread in areas with patchy grass cover.

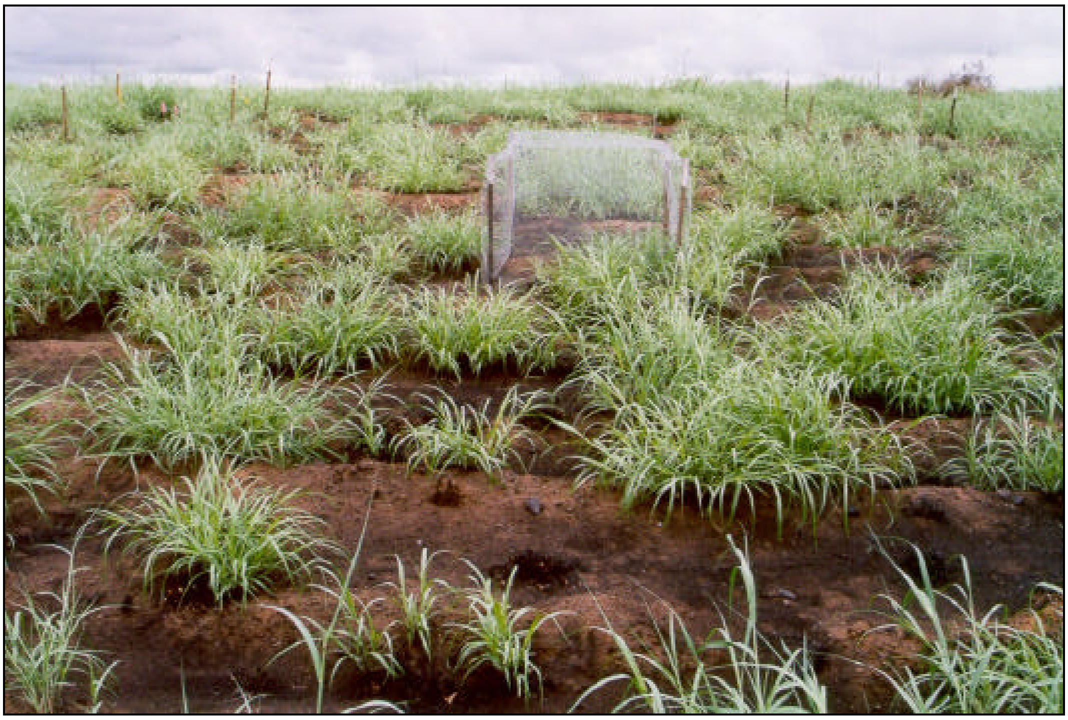

Plate 6. Catchment C in March 2000 showing regrowth from existing tussock bases and tillers.