Development of reconstructed soils and vegetation communities at a central Queensland coal mine: a preliminary investigation of twelve years of monitoring

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Abstract

Soil profile reconstruction during the reclamtion of mine waste dumps and establishment of sustainable vegetative covers are well recognised rehabilitation practices and targets of the modern mining industry. In the central Queensland coalfields, many on-site and laboratory trials have characterised the Tertiary spoil requiring rehabilitation and assessed subsequent vegetation establishment. However, relatively few studies have investigated longer-term development of these ecosystems. In 2003, the re-monitoring of a Tertiary spoil trial at Saraji Mine provided the opportunity to reflect on 12 years of soil and vegetation development. The trial consisted of four media treatments: sodic, alkaline Tertiary clay spoil; saline, acid coal rejects overlying spoil; and two depths (10 cm and 30 cm) of topsoil overlying spoil. These were sown with two vegetation treatments: a native tree/shrub mix (5.16 kg ha⁻¹) with and without improved pasture grasses (2 kg ha⁻¹). Twelve years from establishment, preliminary investigation has shown that where poor plant growth resulted from adverse media characteristics, salts have concentrated in the soil surface due to capillary rise. In the most severe case, on Tertiary spoil, mean ground cover (22%) corresponded with an increase in mean electrical conductivity at 0-1 cm soil depth (1.5 to 7.8 dS m⁻¹, 1991-2003). However, on media where good vegetation cover established (90%), such as on the 30 cm topsoil treatment, the salt concentration at 30-40 cm depth for one site was reduced (1.2 to 0.6 dS m⁻¹, 1995-2003). Identification and interpretation of these trends and their relationship to initial media characteristics and vegetation treatments will assist site environmental officers with long-term post-mining management of the central Queensland Tertiary spoil landscape.

Key Words

Rehabilitation development; ecosystem trends; mining landscape

Introduction

Soil profile reconstruction during the reclamtion of mine waste dumps and establishment of sustainable vegetative covers are well recognised rehabilitation practices and targets of the modern mining industry. In the central Queensland coalfields, many trials have characterised the Tertiary spoil (derived from rock of the Tertiary period) requiring rehabilitation and assessed subsequent vegetation establishment. However, there have been relatively few studies investigating the longer-term development of these ecosystems.

To investigate these ecosystem trends, Odum (1969) suggested using major structural and functional characteristics that show change in a developing ecosystem. These characteristics, or indicators, have been further developed by many authors (Aronson et al. 1993; Smyth and Dearden 1998; Walker and Reuter 1996) and cover a range of factors describing the soil health, productivity and biodiversity of an ecosystem. When using these indicators to assess ecosystem changes, no single parameter provides the best index of the ecosystem condition, and although many parameters can be considered for inclusion in restoration success criteria, some can be ambiguous or hard to measure and should therefore be excluded (Hobbs and Harris 2001; Smyth and Dearden 1998). Thus, (Dalal et al. 2003) stipulated that indicators used in a monitoring program should have a well understood meaning, be easily repeatable, and yield valuable information about desirable or undesirable changes.

By understanding ecosystem trends, the rehabilitation decision-making process is assisted (Wilkins et al. 2003). Those monitoring programs that focus on the trajectory or dynamics of the successional development rather than on the end-product provide an accurate representation of success in dynamic systems, and are preferable to the once common ‘snapshot’ monitoring programs (Smyth and Dearden...
1998). Therefore, identifying the trends for one longer-term trial in the region can provide a valuable tool to surrounding operations that have similar climatic conditions and similar overburden media.

The objective of this study was to describe the longer-term development of a rehabilitation trial established on an open cut coal mine in central Queensland with four media treatments and two vegetation treatments providing a range of ecosystem start-points. The indicators selected for inclusion in the initial assessment in 2003 were ground cover, tree and shrub density, tree heights, foliage projective cover (FPC), soil pH, and electrical conductivity (EC). These were chosen for their ease of measurement and interpretation, repeatability, and inclusion in previous trial assessments (Bell et al. 1991a; Bell et al. 1991b; Bell et al. 1992; Grigg and Catchpoole 1999; Grigg et al. 1997).

**Methods**

**Study site**

Saraji Mine is located within the Bowen Basin at 22°24’S, 148°18’E. This site experiences sub-humid, sub-tropical conditions with an average annual rainfall of 610 mm. The rainfall is summer dominant and highly variable between years. Mean evaporation for the region exceeds precipitation in every month where the greatest deficit between the two occurs during spring and early summer (McLennan 1994).

**Trial design**

Three sites at the mine operation were selected, based on initial spoil chemical characteristics. These were located in areas adjacent to the Acacia, Coolibah and Ebony pits (Bell et al. 1991). Spoil at the Acacia site was moderate to strongly alkaline and moderate to strongly saline. At Coolibah, the spoil was a neutral pH and extremely saline, and at Ebony, the spoil was strongly alkaline and moderate to strongly saline.

The trial, established in April 1991, was designed in a split plot layout with media treatments as whole plots, and vegetation treatments as sub plots. At each site, treatments were established on 5 m × 5 m plots with a 0.5 m buffer along each side to provide an internal 4 m × 4 m measurement area. Four media treatments were included in the trial: bare Tertiary spoil, coal reject over spoil (a nominal 7.5 cm depth), and the loamy sand A horizon from a solodised solonetz at 10 cm and 30 cm depth over spoil. Two vegetation treatments were selected for the trial, namely a native tree/shrub mix (5.16 kg ha⁻¹) with and without improved pasture grasses (2 kg ha⁻¹). Each vegetation treatment was direct seeded on four randomly allocated plots within each media treatment. Plots were fertilised with 100 kg ha⁻¹ nitrogen and 50 kg ha⁻¹ phosphorus.

**Data collection**

The trial was monitored in August 1991, May 1992, May 1995, May 1999 and May 2003. In the most recent assessment, vegetation and soil attributes were collected from 96 plots of the trial. Vegetation was assessed through measurements of percent ground cover, percent FPC, and native tree density and height. Soil was sampled using a corer, 38 mm in diameter, to a depth of 75 cm. Each core was divided into 0-1, 1-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, and 70-75 cm depth increments. Samples were analysed for EC and pH using a 1:5 soil:water suspension (Rayment and Higginson 1992).

**Statistical analysis**

All statistical procedures were carried out using GenStat 6.1 (Genstat 2002). Univariate analyses of variance were performed to determine the significance of the effects of soil and vegetation treatments on each measured parameter. Where the analysis of variance identified significant interactions or treatment effects, treatment means were compared using Fisher’s protected least significant difference test (LSD).

To stabilise the variance prior to analysis, a logarithmic transformation was used for tree density and soil EC data, while percent data (ground cover and foliage projective cover) utilised an arcsin transformation (arcsin(x/100)½).

**Results and discussion**

**Ground cover**

Since trial establishment in 1991, mean ground cover (live+litter) on all media and vegetation treatments has increased, with the greatest cover observed on the 30 cm and 10 cm Soil treatments and the least on the Coal Reject and Spoil treatments (Figure 1). In 2003, this trend persisted and a significant interaction
between vegetation treatments and media treatments for ground cover ($F_{3,8}=10.35, p=0.004$) was observed, indicating differing responses of the two vegetation types to the four media treatments.

The only significant difference observed in 2003 was on the Coal Reject treatment, where ground cover on Natives Only plots was significantly greater than on the Natives + Pasture plots. No other media treatment or vegetation treatment exhibited significant differences in 2003, although the difference between Coal Reject and 30 cm Soil treatments under Natives + Pasture treatments (Figure 1a) was close to significant. While the ground cover differences between media (Figure 1) are not statistically significant due to the large variability, it is noteworthy that the media treatments appear to have separated into two groups after the 1995 monitoring. This division is potentially based on the nutrient characteristics and substrate water availability. Since 1995, the rate of increase for ground cover has slowed for all media except Coal Reject, particularly for the most recent assessment period (1999-2003). This potentially indicates that an equilibrium (excepting Coal Reject) has been reached, following Odum’s (1969) theory of steady states in ecosystem development.

![Graph](image-url)

**Figure 1.** Mean ground cover at Saraji Mine (1991–2003) for (a) Natives + Pasture and (b) Natives Only treatments on four media treatments.

**Tree and shrub density, height and canopy cover**

Since 1995, mean tree density increased on all media for both vegetation treatments except Natives + Pasture treatments on Spoil. There was an initial flush of seedlings recorded in the first monitoring (six months after establishment) on the Natives Only plots, the majority of which did not survive the first summer. Another flush of seedlings was captured in the May 2003 assessment (data not shown), predominantly *Acacia salicina* seedlings within the 0-20 cm height category, indicating recruitment by this species. This flush of seedlings corresponded to a wet February 2003 (267 mm) followed by months of minimal rainfall. As tree seedling survival in grasslands has been shown to be inversely related to net water supply, and to be strongly influenced by the intensity of competition from herbaceous vegetation (Davis *et al.* 1998), it was hypothesised that the majority of seedlings monitored in 2003 would not survive the pasture competition in combination with the dry 2003/04 summer. This was confirmed visually on-site in May 2004 and therefore, seedlings below 20 cm were considered transient and not indicative of the true treatment effects.

When the density data excluding seedlings <20 cm was analysed, it was found that density in 2003 for the Natives Only treatments was significantly greater than on the Natives + Pasture treatments ($F_{1,8}=6.09, p=0.039$) across all media (Figure 2). Density was greatest on the Coal Reject treatment but despite the substantial difference between the mean density on Coal Reject and the other three media, the media effect was not significant ($p=0.411$). This was due to the restricted number of sites resulting in a relatively non-powerful test (six and eight degrees of freedom for media and vegetation respectively). Since 1995, mean densities remained relatively stable for all media treatments, except Spoil under Natives + Pasture and Coal Reject under both vegetation treatments. Although density on Spoil decreased over time, in 2003 it reached a level similar to that of other topsoil treatments. Results over time for topsoil and Coal Reject treatments were consistent with the findings from the ground cover data; that is, while topsoil plots had reached equilibrium, the Coal Reject continued to increase.
Canopy height increased on all treatments since trial establishment. In 2003, the tallest tree at the Acacia site was 6.8 m (Natives Only on Coal Reject), at the Coolibah site was 7.3 m (Natives + Pasture on Coal Reject) and the two tallest at Ebony site were 14.0 m and 15.4 m (Natives Only on Spoil and 30 cm Soil respectively). Correspondingly, FPC also increased on all media and vegetation plots since trial establishment. In 2003, for Natives + Pasture treatments Spoil had the greatest mean FPC (Figure 3a), while for Natives Only treatments, the greatest mean FPC was on Coal Reject (Figure 3b). A comparison between the vegetation treatments showed that the FPC on Natives Only treatments were significantly greater than on Natives + Pasture treatments ($F_{1,8} = 8.36, p=0.020$) across all media. There were no significant media differences ($p=0.803$).

![Figure 2. Mean tree density (stems/ha) for Saraji Mine, 1991-2003, excluding seedlings (0-20 cm) for (a) Natives + Pasture and (b) Natives Only treatments on four media treatments.](image)

![Figure 3. Mean Foliage Projective Cover (%) for Saraji Mine (1991-2003) for (a) Natives + Pasture and (b) Natives Only treatments on four media treatments.](image)

**Soil pH**

A comparison of pH under the four media treatments, taking into account the natural variation and the small seasonal variations expected at the site, showed there was little difference between 2003 and previous years. Changes in pH within the surface 0-10 cm on disturbed soils can occur over time by processes such as weathering, net N mineralisation and subsequent nitrification following the addition of organic substrate with plant residue return, and to a limited extent through root mediated pH changes (Edraki et al. 2001; Hinsinger et al. 2003; Paul et al. 2001; Wilden et al. 1999). To assess soil surface pH changes, the upper 0-10 cm of the soil profiles from the trial were examined (Figure 4).
It was found that for both vegetation types in 2003, Coal Reject had a significantly smaller pH ($F_{3,6}=17.53, p=0.002$) than the Spoil, 10 cm Soil and 30 cm Soil treatments in the surface 0-10cm soil (Figure 4). There were no significant differences between the pH on Spoil, 10 cm Soil and 30 cm Soil. Comparison of the vegetation treatments showed that the surface soil pH (0-10cm) under Native + Pasture treatments and that of the Natives Only treatments were not significantly different ($p=0.836$). Since trial establishment, there have been minimal changes in pH on these media, although the accumulated surface organic matter observed on these plots could have been expected to result in some level of nitrification and therefore acidification. The lack of surface acidification may be due to suppression of N mineralisation in this low rainfall region (Paul et al. 2001).

Soil electrical conductivity

The mean EC in 2003 varied both through the profile and across the sites for each media treatment, and in particular for the surface 0-20 cm of the Spoil treatments (Figure 5). At depths greater than 50 cm, the mean EC showed little variation between the treatments. In the surface soil, mean EC was the least on 30 cm Soil treatments, followed by 10 cm Soil and Coal Reject, while mean EC was greatest on the Spoil treatments.

Mean surface soil EC (0-10 cm depth) across all treatments in 2003 was greatest for Spoil (1.64 dS m$^{-1}$) followed by 10 cm Soil (0.28 dS m$^{-1}$) and Coal Reject (0.27 dS m$^{-1}$), with the smallest EC found on the 30 cm Soil treatment (0.09 dS m$^{-1}$) (Figure 6). Analysis indicated significant media effects ($F_{3,6}=5.10, p=0.043$) with mean surface EC for Spoil significantly greater than that of 30 cm Soil across both...
vegetation types. The differences between the other media were not significant. In a comparison of vegetation treatments, it was found that the EC of the surface 0-10 cm was significantly greater under the Natives Only treatments than under the Natives + Pasture treatments (F_{1.8}=7.53, p=0.025) across all media.

Over time, there was little EC variation at the soil surface (0-10 cm) for 30 cm and 10 cm Soil treatments, indicating that there has been no accumulation of salts at the soil surface for these topsoil treatments. Mean surface EC on Coal Reject decreased, and Spoil values fluctuated (Figure 6). The decrease in the mean 0-10 cm EC for Coal Reject across all sites, indicated possible removal of salts from the surface soil, similar to that found on Coal Reject at Curragh Mine (Edraki et al. 2001). It would be expected that due to the large coarse fraction contained in Coal Reject, this media has a greater infiltration rate than that of the other media which would assist leaching of salts, and therefore in the longer-term improve conditions for plant-growth. Although ground cover for this media was at the lower end of observed data (Figure 1), the cover continued to increase, whereas cover on all other media appeared to have stabilised.

In contrast to Coal Reject, the Spoil surface EC fluctuated over time and displayed large variation between sites (Figure 6). By examining each site separately, it was found that at two sites (Acacia and Ebony sites) Spoil EC in the surface 0-10 cm decreased marginally over time, with little fluctuation. At the third site (Coolibah) there was a large EC increase in the 0-10 cm soil, particularly in the 0-1 cm soil which increased from 1.5 dS m\(^{-1}\) in 1991 to 7.3 dS m\(^{-1}\) in 2003 for the Natives + Pasture treatment and from 1.9 dS m\(^{-1}\) to 7.8 dS m\(^{-1}\) for the Natives Only treatment. This media was initially the most saline and sodic spoil material of all three sites, and the increase in surface salts on the Spoil treatment also corresponded to the least vegetation cover (22%) of all the treatments. This media is becomingly increasingly unfavourable for plant growth, as although trial ground cover had been static since 1995, the last monitoring period saw a decrease in the live cover and an increase in the litter component. The EC fluctuations in the intervening years observed at this site showed some correspondence with site rainfall means, where dry years preceding monitoring resulted in a greater mean surface EC, and preceding wetter years resulted in a reduced mean EC. Additionally, the large standard error of the yearly mean in the dryer years indicated the EC was highly variable between sampling points; potentially due to the variability in the vegetative cover leading to an irregular pattern of salt accumulation.

![Figure 6](image_url)

**Figure 6.** Mean electrical conductivity of the surface (0-10 cm) soil at Saraji Mine (1991-2003) for (a) Natives + Pasture and (b) Natives Only treatments on four media treatments.

When 2003 EC results below the Soil:Spoil boundary (30-40 cm) were analysed for all media, it was observed that EC was least on 30 cm Soil plots, followed by 10 cm Soil and Coal Reject plots, and greatest on Spoil plots. The 30 cm Soil EC was significantly less than all other media treatments, while the Coal Reject EC was significantly less than that of the Spoil treatment (F_{1.8}=49.00, p<0.001). There was no significant difference between EC under Natives + Pasture and Natives Only treatments (p=0.983). A comparison of these media over time showed that EC under both the Coal Reject and the 30 cm Soil decreased, while EC under Spoil and 10 cm Soil appeared to remain static (Figure 7).
Figure 7. Mean electrical conductivity below the spoil interface (30-40 cm) at Saraji Mine (1991-2003) for (a) Natives + Pasture and (b) Natives Only treatments on four media treatments.

Continued removal of salts at depth on the Coal Reject indicated water movement through the Reject:Spoil interface. In contrast, the 10 cm Soil treatment, which overlayed the spoil at approximately the same depth as the Coal Reject, did not show a similar trend. The most pronounced salt decrease at 30-40 cm depth was again the Coolibah site on the 30 cm Soil treatment, where EC decreased from 1.2 and 1.0 dS m\(^{-1}\) in 1995 to 0.59 and 0.60 dS m\(^{-1}\) in 2003 for Natives + Pasture treatment and Natives Only treatments, respectively. Of the treatments at Coolibah, the 30 cm Soil plots had the greatest ground cover on each monitoring occasion, attaining 90% in 2003.

Preliminary investigations into the development of these ecosystems indicated that the two topsoil treatments were close to reaching a steady state, with ground cover, tree density (>20 cm), soil surface pH (0-10 cm) and soil surface EC (0-10 cm) values having stabilised. There were indications from the increasing FPC trend and the increasing canopy height that slower changes within the ecosystem continued to occur. Both topsoil treatments appeared to restrict net upward salt movement, while the 30 cm Soil treatment showed additional evidence of salt movement down through the profile (30-40 cm) over time. Salt movement at depth for the shallower 10 cm Soil treatment appeared to be static. These two topsoil treatments continued to support a greater ground cover than the Spoil and Coal Reject, although this greater grass cover provided competition for native tree and shrub seedling emergence and restricted subsequent survival.

In the case of the Spoil treatment, some attributes indicated a move towards equilibrium; ground cover, soil surface pH (0-10 cm) and EC at depth (30-40 cm). In contrast, tree density (>20 cm) decreased, FPC increased, and surface EC (0-10 cm) fluctuated. Stem density decreased to a point similar to that of topsoil treatments, and suggested natural thinning had occurred. Fluctuating soil 0-10 cm EC was dominated by the Coolibah site results, and it was clear that this strongly saline and sodic media in the unamended state continued to become increasingly unfavourable for plant establishment or growth. Topsoil treatments overlying the Spoil at the Coolibah site appeared to achieve vegetative growth comparable to that of the Ebony and Acacia topsoil treatments, suggesting that even a shallow surface amendment assisted in vegetation establishment and ecosystem development on hostile media. Exclusion of the Coolibah site Spoil results showed that the Acacia and Ebony site Spoil treatments appear to be approaching that of the topsoil treatments, although this requires further investigation. It can therefore be hypothesised that unamended media with initial salinity and sodicity characteristics similar to the Coolibah Spoil are unable to support sustainable plant growth.

From the data available, the Coal Reject treatment had not reached steady state with respect to vegetation development after 12 years, potentially indicating that this Coal Reject ecosystem was developing at a slower rate than the other media ecosystems. Continuing increases in ground cover, tree density (>20 cm) and FPC were observed over time, while EC at both the 0-10 cm and 30-40 cm depths decreased over time. It is likely that the characteristics of the Coal Reject initially limited pasture establishment in comparison to the topsoil treatments, but over time the physical nature of this material may have encouraged greater infiltration, which in turn may have improved the media for plant growth.
Vegetation treatment differences by 2003 were in most cases not significant; and factors such as pasture invasion into the Natives Only plots contributed to certain treatments reaching similar end-points. There were, however, some exceptions to these similarities that developed over time. Natives Only treatment values were significantly greater than Natives + Pasture treatments on Coal Reject for ground cover, tree density (>20 cm), FPC and soil EC (0-10 cm). Other significant differences between vegetation treatments were observed for FPC and surface EC (0-10 cm) results on all media, where Natives Only treatment values were significantly greater than Natives + Pasture treatment values. Further research is required to investigate the soil EC and ground cover relationships.

**Conclusion**

Preliminary investigations indicated that many of the attributes for the two topsoil treatments were close to steady state. In contrast, the vegetation attributes on the Coal Reject continued on an upward trend, indicating that this ecosystem was developing at a slower rate than that of the other media treatments. The Spoil treatment attributes at the Acacia and Ebony site approached a steady state similar to that of the topsoil treatments, while the attributes for the strongly saline and sodic Spoil at the Coolibah site indicated that this material was increasingly unfavourable for plant establishment and growth. Importantly, the topsoil treatments overlying this strongly sodic and saline Coolibah site spoil appeared to achieve vegetative growth comparable to that of the topsoil overlying spoil at the Ebony and Acacia sites, suggesting that even shallow topsoil application, although not as effective as the deeper application in promoting salt movement down the profile, assisted in vegetation establishment and ecosystem development on hostile media.

It was evident that the initial surface media characteristics influenced both the potential of the system and the rate of development of the system. This preliminary investigation has highlighted the need for further analyses, including an understanding of productivity (such as biomass) and additional soil parameters (such as infiltration) to better identify these influences. Furthermore, given the nature of the ecosystems developing on the post-mined landscapes and the stability as evidenced by trends in vegetation development, broader questions can now be posed. Are such ecosystem outcomes acceptable and appropriate endpoints to stakeholders, are they ecologically robust, and where do such systems sit within a local/regional context are all questions that can now be asked and assessed.

**Acknowledgements**

This research was funded under a Coal Trust Scholarship provided through ACMER with operational support from BHP Billiton Mitsubishi Alliance Saraji Mine and Brisbane offices, the Centre for Mined Land Rehabilitation (CMLR) and the Sustainable Minerals Institute (SMI) at the University of Queensland. Thanks to Rosemary Kopittke for assistance with the statistical analyses and the CMLR staff, in particular Craig Lockhart, for their assistance in the field.

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