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Soil chemical and physical constraints to pasture productivity on rehabilitated land after bauxite mining

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Abstract

The reconstruction and rehabilitation of soil profiles to facilitate sustainable land use as a pasture, requires careful planning and management. Pastures are among the most common form of land rehabilitation after mining, but the productivity of these pastures is less than that of comparable unmined land. Here we assessed the soil properties and pasture production on recently rehabilitated farmland after bauxite mining, which are considered to have diminished productivity in comparison to adjacent unmined grassland. This was to understand the limitation to achieving levels of soil fertility, pasture productivity and sustainability similar to those of the pre-mined landscapes. After comparing soil pit profile descriptions, we assessed several *soil and plant parameters to identify the constraints to pasture growth.*

Several edaphic parameters differed between unmined and rehabilitated soils, including pH, salinity, particle size distribution, soil strength, soil organic carbon and cation exchange capacity. Both rehabilitated and unmined areas had some deficiencies in plant available nutrients in both topsoils and subsoils. Many of the edaphic parameters that showed significant differences were likely due to the mixing of materials during excavation, handling and re-spreading as part of the mining and rehabilitation process.

The pasture plants also exhibited different responses between rehabilitated and unmined soils. Root mass penetration through the rehabilitated profiles was generally less than the unmined profiles. Differences in pasture dry matter production were identified between the mined and unmined areas. No significant difference was found in pasture species composition on the rehabilitated sites.

In summary, no single constraint to pasture production on the rehabilitated land was identified. However, the handling and mixing of the soil materials leading to the creation of impenetrable zones may be an important aspect. In addition, organic matter concentrations remain low in rehabilitated topsoils and fertile topsoils were likely diluted through the disturbance and the profile reconstruction process. These three factors may be attributed to the underlying cause of reduced pasture production.

Keywords: *soil, plant, roots, pasture, grasslands, nutrients, root penetration, rehabilitation, nutrients, soil strength, modulus of rupture*

1 Introduction

Post-mining landscapes, designed to match stakeholder expectations, are often aligned with the pre-mining landscape practices. The reconstruction and rehabilitation of soil profiles to facilitate sustainable land use such as a pasture, requires careful planning and management. Pastures are among the most common form of land rehabilitation after mining (e.g., Bennett et al., 2021), but the productivity of these pastures may be lower than comparable to unmined land, due to a number of notable differences (Grigg et al. 2000). Bauxite mining results in the removal of several metres of the soil profile underlying the surface soil horizons. During rehabilitation after mining, the salvaged surface soils and overburden are redeposited as 'layers' on the lowered, truncated profile. These layers often resemble the soil horizons found in the undisturbed profiles. However, some properties of the reconstructed soil profiles are likely to differ from those existing prior to mining, especially in terms of key physical parameters and chemical fertility affecting plant growth. Many regolith materials, once disturbed, brought to the surface and redeposited, will have significantly different characteristics to those in their former undisturbed geological setting.

A number of bauxite mines exist on lateritic profiles typical of the eastern side of the Darling Range of Western Australia (McArthur 1991, Mulcahy 1960, Soltangheisi et al., 2023, Tibbett 2010). The origin, geology, mineralogy and chemistry of these profiles have been described elsewhere (e.g. Gilkes et al. 1973, Mulcahy 1960, Mulcahy et al 1972 and Soltangheisi et al. 2023). The effects of the removal and reconstruction of these profiles on the physical and chemical attributes of the soil, and the associated implications for productivity and sustainability have scarcely been investigated. Ward (2000) found no soil chemical barriers to regeneration of forest species on a rehabilitated bauxite mine on the Darling Plateau, however there is a paucity of published work that investigates soil physical conditions, root development and concomitant pasture productivity for such rehabilitated profiles.

The rehabilitation was aimed at replicating the pre-mining land use which included a mosaic of pasture and native vegetation. The study aimed to understand the limitation to achieving comparable levels of soil fertility (physical and chemical soil properties) and pasture productivity to those of the pre-mined landscapes. Unlike other studies (e.g.,Bennett et al., 2021; Grigg et al. 2000) that compared rehabilitated sites to adjacent pastures, we were able to assess the effect of several single pasture fields cut in two and rehabilitated simultaneously. We assessed numerous soil and plant parameters to identify potential constraints to pasture growth after mining. Specifically, the capability of existing reconstructed soil profiles was assessed, that supported pasture at similar levels of productivity to that expected in un-mined pasture soils.

2 The mining environment and land rehabilitation

The restoration goal, agreed upon with the landowner, was to provide rehabilitated land for the grazing of pastures. Rehabilitation standards aimed to re-establish the pre-mining land capability (the ability of the land to support a type of land use without causing damage) with three specific objectives. These included (i) a stable and safe landscape, (ii) no increase in the potential risk of wind and water erosion, and (iii) compatibility with the surrounding landscape. Of importance, the land capability of the disturbed area should enable pre-mining productivity levels.

2.1 Site description and rehabilitation process

The study area is located on the ancient highly weathered soils on the western edge of the ancient Great Plateau of Western Australia on the granitic shield of the Yilgarn craton (2.5 Gya). The area is characterised by a Mediterranean climate with hot, dry summers and cool, mild winters. The average annual rainfall is 740 mm per year of which 80% is received between May and October in the Austral winter.

The project area is located on the eastern edge of the Darling Plateau, approximately 140 km south-east of Perth, the state capital. The area is characterised by two north-south undulating laterised ridges separated by a mildly salt affected drainage line. The ridge and upper slopes are characterised by sheets of duricrust, shallow, gravely sandy loams underlain by duricrust and have been left largely uncleared. The steep to gently undulating slopes consist of shallow, gravel soils on the upper slopes grading into deep gravely loams on the mid slopes and deep gravely loamy sands on the lower slopes. All these soils are underlain by duricrust. These soils are prone to water and wind erosion, particularly on the lower slopes where there is a relatively high sand content. The valley floor, located between the ridges consists of gravely clay loams and lateritic clays essentially of alluvial origin. The exploited bauxite reserves were contained within the ridge and upper - mid slope landforms.

2.2 Agricultural land

The area of land that was mined had previously been cleared of remnant vegetation for the establishment of pasture. The pasture is a mixture of annual species including ryegrass (*Lolium rigidum*), subclover (*Trifolium* *subterraneum*), barley grass (*Hordeum spp*.), silver grass (*Vulpis* spp.), brome grasses (*Bromus* spp.), capeweed (*Arctotheca calendula*) and storksbill (*Erodium* spp.).

2.3 Earthworks, soil stripping and rehabilitation

In areas of pasture, sub-soil comprised a gravel beneath the topsoil to a depth of 50cm. Sub-soil was removed and stockpiled separately from topsoil and returned in reverse order after mining. Large rocks left after mining were buried at least two metres below the final land surface. Pit floors were cross-ripped at 1m intervals to a target depth of 1.5m to relieve compaction. The soil was ripped during the summer and early autumn when dry conditions maximize soil fracture (Lardner and Tibbett 2013). The entire former pit was scarified on the contour after the gravel and topsoil has been returned.

Gravel and topsoil were returned separately and in sequence to a profile depth of at least 80cm. Care was taken that topsoil from areas previously under pasture were returned exclusively to areas being rehabilitated to pasture.

2.4 Pasture establishment and grazing management

Rehabilitation to pasture was carried out in a two-stage process. There was an initial cropping phase of two years with oats undersown with sub-clover followed by the establishment of a permanent pasture of sub-clover and annual ryegrass. Pasture seed was sown as soon as possible after the break of the season in the first year of the pasture phase at the following rates with a mix of Avon ryegrass 15 kg/ha, Dalkeith sub-clover 15 kg/ha, Junee sub-clover 10 kg/ha and York sub-clover 10 kg/ha. The clover seeds were lime pelleted and inoculated with the appropriate strains of nitrogen fixing rhizobia. A basal fertiliser application of 400 kg/ha of Super Potash (5:1) (typical analysis 7.6% phosphorus 8.1% potassium) was applied in the first and second year of the pasture establishment.

Rehabilitated pastures were not grazed until the vegetation was 10 cm high. Grazing was managed so that a minimum pasture height of 5 cm was maintained. Stock was removed on or before the last week in September to ensure adequate seed set. Stock was not re-introduced until January.

3 Materials and methods

3.1 Profile descriptions

During the second season of pasture growth four soil pits were excavated for profile descriptions. Two pits were within reconstructed soil profiles and two in adjacent unmined areas. Pits were excavated to a maximum depth of 2 metres, although in most cases, lateritic caprock or waste rock prevented excavation to the target depth. The soil profiles were described in terms of dimension, structure and colour, with bulked and undisturbed samples collected for determination of the chemical and physical characteristics of each horizon or reconstructed soil layer. A measurement of root growth was taken in each profile using a $1m^2$ grid, with a score of root growth given for each $10cm^2$. Measurements of pH and electrical conductivity were made on a 1:5 soil:water extract, with pH measurements also made for a 0.01M CaCl2 extract (Rayment & Higginson, 1992).

3.2 Soil physical and chemical characteristics

For soil sampling a total of 14 soil pits were excavated (including the 4 above), with the 8 pits within reconstructed soil profiles and 6 in adjacent unmined areas. Replicated samples from each disturbed profile layer and undisturbed soil horizon were taken for physical and chemical analysis. Dry bulk density measurements, where possible, were taken from undisturbed core samples (Klute 1986), 7 cm deep, with a diameter of 7cm. In most cases however, the high gravel contents prevented the collection of intact core samples. Bulk density was therefore determined using the clod method as described in McKenzie et al, (2002). A measure of soil strength and the tendency of each material to hardset were taken using a modified

Modulus of Rupture test (Aylmore & Sills 1982, Harper & Gilkes 1994). Particle size distribution was determined using the pipette method as described in Klute (1986). Soil nutrient status (N, P, K, S and Fe) of samples taken from each profile was measured by CSBP Futurefarm laboratories using the methods described in Rayment and Higginson (1992). P and K were extracted using 0.5M NaHCO3 (Colwell procedure). Organic carbon was assessed using the Walkley and Black (1934) method. Cation exchange capacity was measured using silver thiourea as described in Rayment and Higginson (1992).

3.3 Pasture assessment

Pasture composition and productivity were assessed throughout the growing season with pasture cuts taken in July, September and October. Replicated cuts were taken from the areas around each soil pit which were excluded from grazing using 0.11m2 (33cm x 33cm) quadrats. Cuts were separated into differing species and air dried to determine the dry matter composition. A measure of pasture composition at each site was taken during the September measurements. The top 2-3cm of soil, plus plants, from a 5cm x 50cm area (replicated 3 times), was returned to the laboratory where the plants were washed out of the soil for the determination of plant density of the main species.

3.4 Statistical analyses

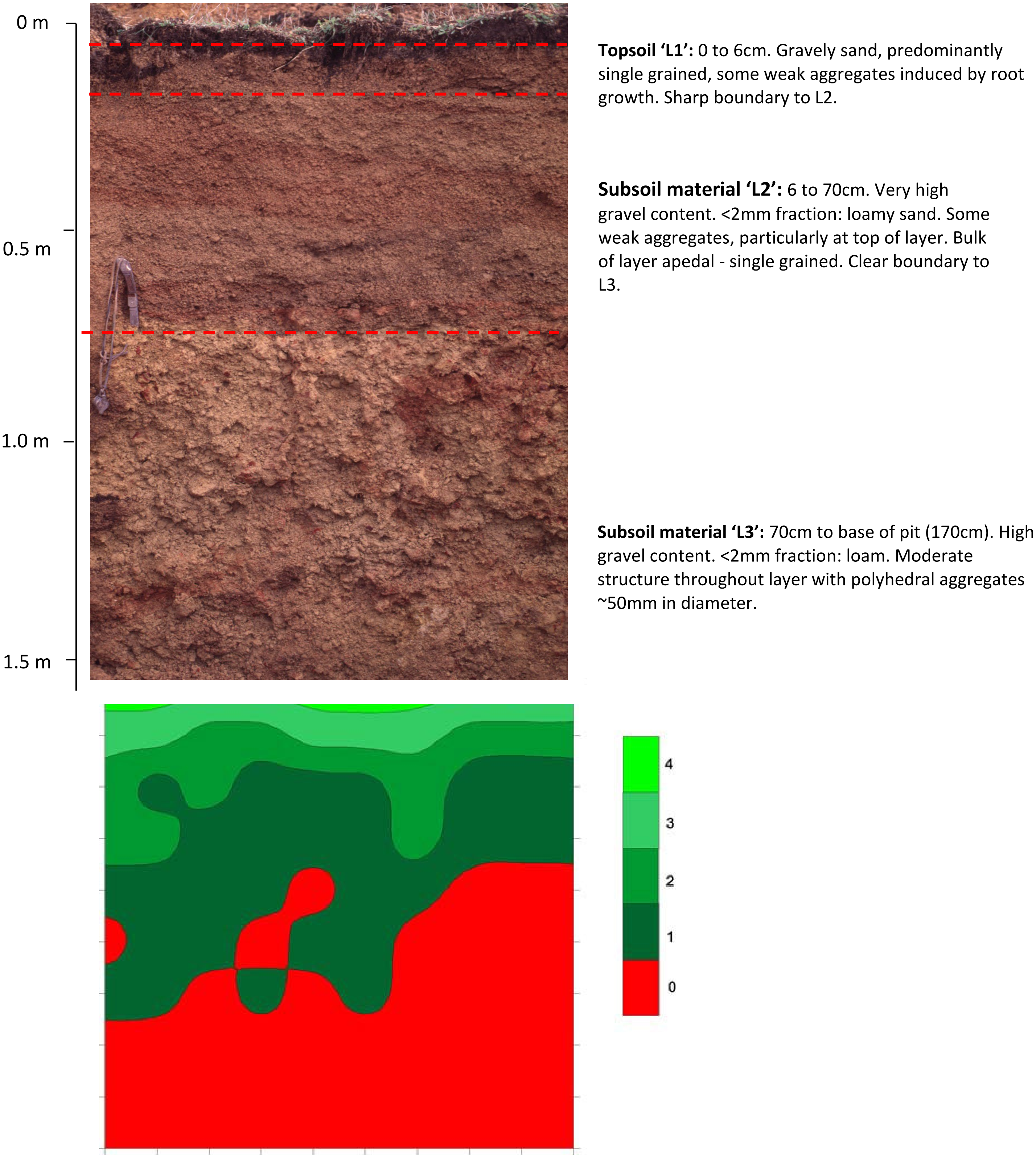
All analysis were performed in SigmaStat version 3.5 which included analysis of variance (ANOVA) and post-hoc test, primarily least significant difference (LSD) test to identify difference between treatment means. All graphs and some descriptive univariate statistics were generated in MS Excel. Significant differences were recognised at the $P < 0.05$ level.

4 Results

4.1 Soil profile descriptions and root distributions

Four profiles were compared, two each from undisturbed natural pasture soils and two from reconstructed soils. The profiles from natural soils use conventional horizon nomenclature, whereas the reconstructed soils were described as layer “L1”, “L2” and so on. Root growth scoring categories were assigned on a visual basis within the categories defined by McDonald et al (1998). Roots observed in each $10cm^2$ were scored **0** for no roots, **1** for few (1 – 10), **2** common (10-25), **3** for many (25-200) and **4** for abundant (>200).

Reconstructed profile 1: Root growth concentrated in top 20cm of profile, throughout L1 and top 10-15cm of L2. Root growth, although sparse, penetrated throughout single grained matrix of L2, decreasing with depth to zero root penetration into "Layer 3" (L3) (Figure 1)



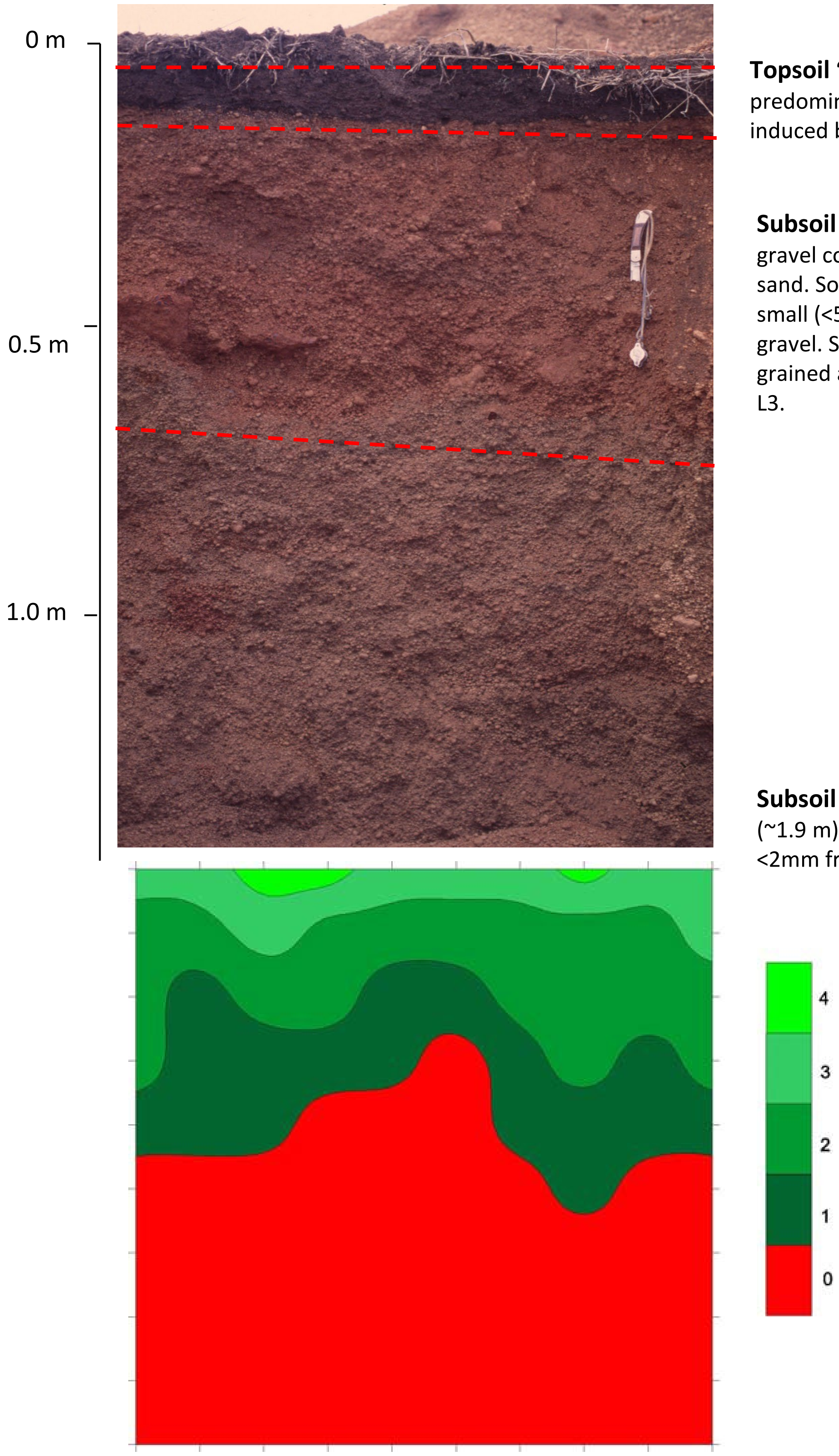
Topsoil 'L1': 0 to 6cm. Gravely sand, predominantly single grained, some weak aggregates induced by root growth. Sharp boundary to L2.

Subsoil material 'L2': 6 to 70cm. Very high gravel content. <2mm fraction: loamy sand. Some weak aggregates, particularly at top of layer. Bulk of layer apedal - single grained. Clear boundary to L3.

Subsoil material 'L3': 70cm to base of pit (170cm). High gravel content. <2mm fraction: loam. Moderate structure throughout layer with polyhedral aggregates ~50mm in diameter.

Figure 1 Soil profile description and root distribution profile maps (1m^2) in reconstructed profile 1

Reconstructed profile 2: Root growth concentrated in top 40 cm of soil profile, with root growth throughout L1 and top 30cm of L2. Some matting of roots evident at boundary between L1 and L2. Root abundance deceases sharply to zero at base of L2 and no penetration into L3 (Figure 2).



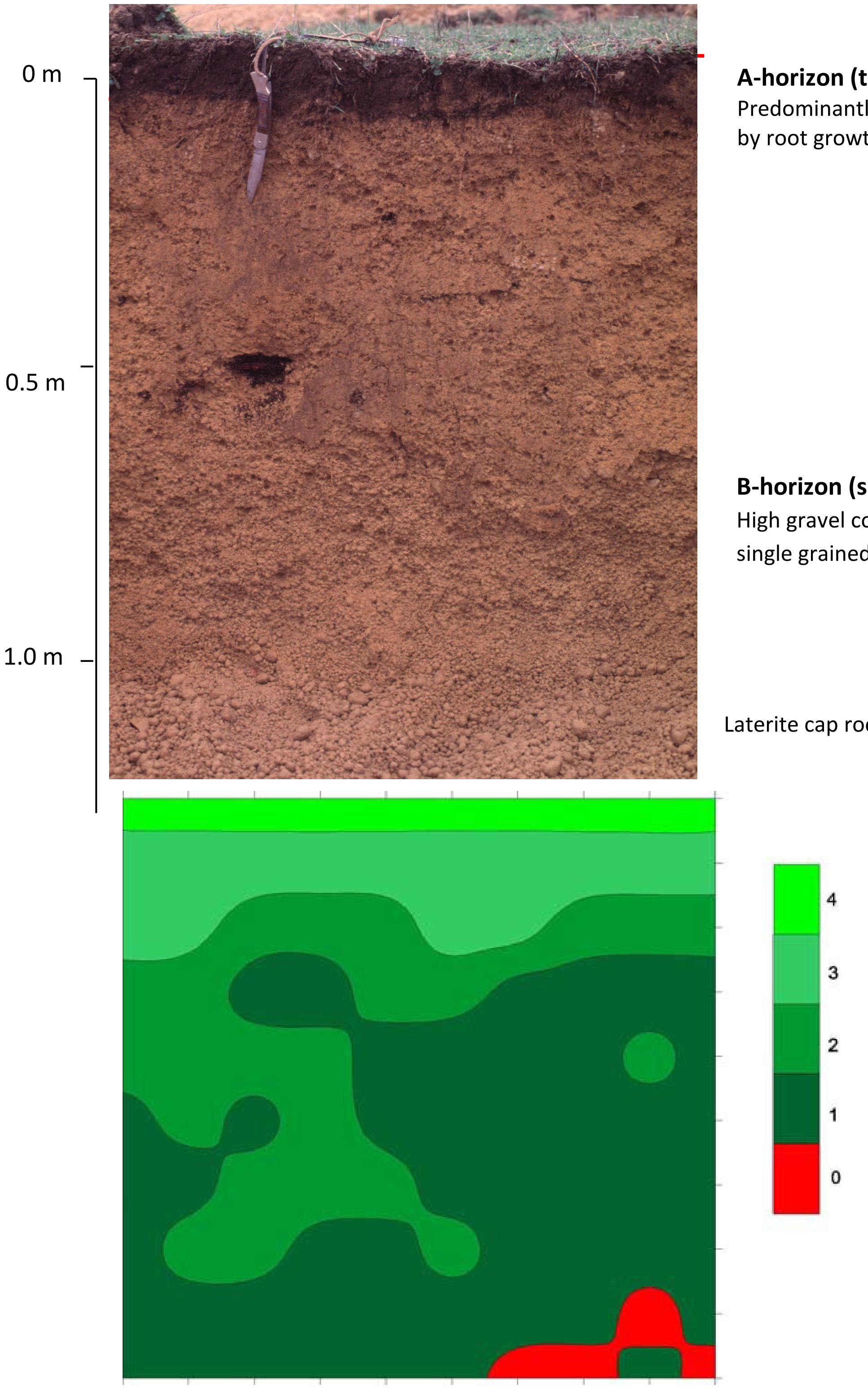
Topsoil 'L1': 0 to 10cm. Gravely loamy sand, predominantly single grained, some weak aggregates induced by root growth. Sharp boundary to L2.

Subsoil material 'L2': 10 to ~ 65cm. Very high gravel content (~80%). <2mm fraction: loamy sand. Some weak structure at top of layer with small (<5mm) polyhedral aggregates between gravel. Structure decreasing with depth to single grained at bottom of layer. Abrupt boundary to L3.

Subsoil material 'L3': ~65cm to base of pit (~1.9 m). Very high gravel content (~84%). <2mm fraction: sand. Apedal, single grained.

Figure 2 Soil profile description and root distribution maps (1m^2) in reconstructed profile 2:

Undisturbed natural profile 3: Root growth, although concentrated in top 40cm of soil profile, extends to base of pit (1.2m). Several old tree roots penetrating laterally across profile in B-horizon (Figure 3).



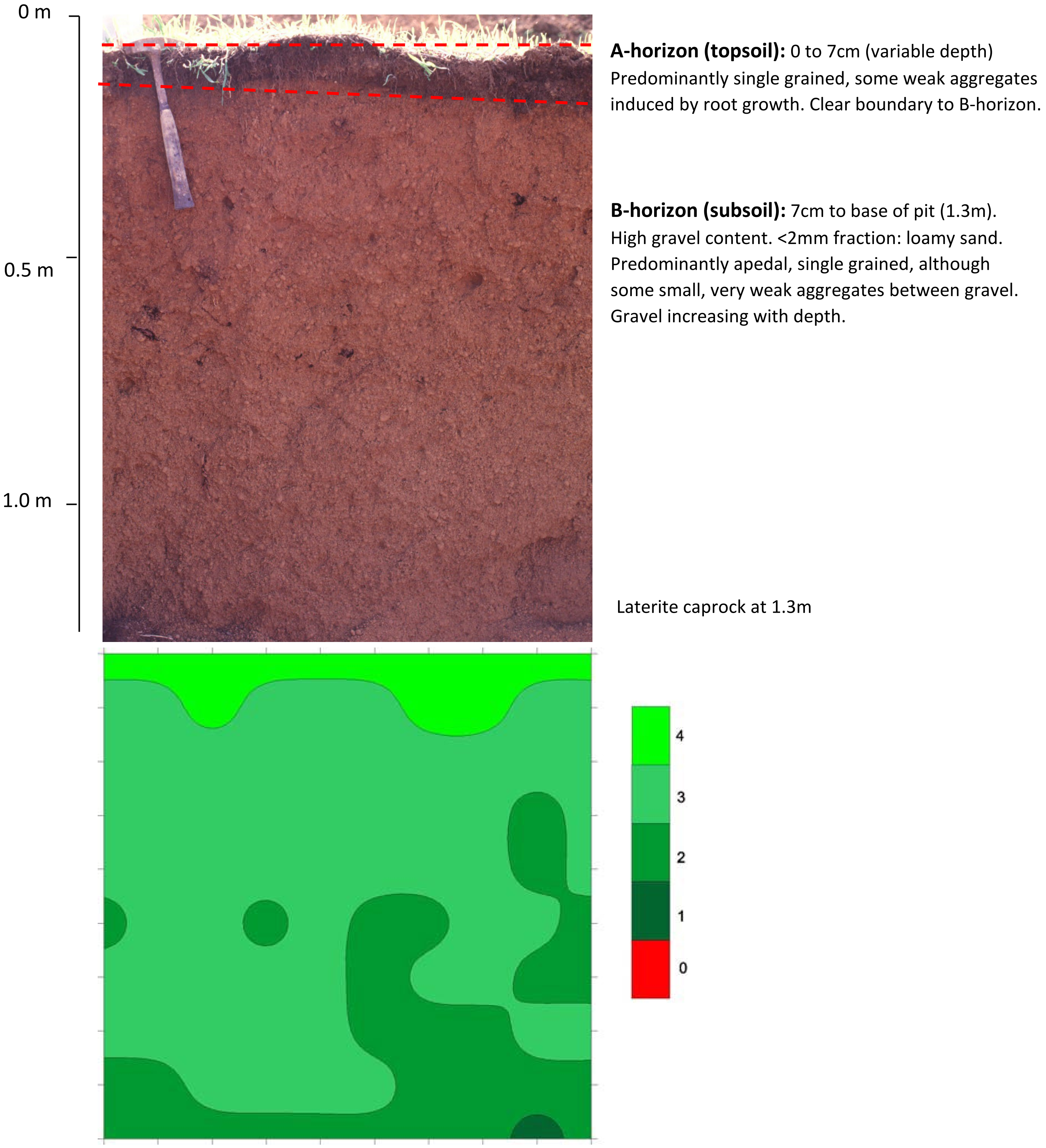
A-horizon (topsoil): 0 to 10cm (variable depth) Predominantly single grained, some weak peds induced by root growth. Clear boundary to B-horizon.

B-horizon (subsoil): 10cm to base of pit (1.2m). High gravel content. <2mm fraction: sand. Apedal, single grained.

Laterite cap rock at 1.2m

Figure 3 Soil profile description and root distribution maps (1m^2) in reconstructed profile 3

Undisturbed natural profile 4 Root growth abundant throughout matrix of topsoil and B-horizon to base of pit (1.3m). Several large roots and old root channels? evident throughout subsoil matrix (Figure 4).



A-horizon (topsoil): 0 to 7cm (variable depth) Predominantly single grained, some weak aggregates induced by root growth. Clear boundary to B-horizon.

B-horizon (subsoil): 7cm to base of pit (1.3m). High gravel content. <2mm fraction: loamy sand. Predominantly apedal, single grained, although some small, very weak aggregates between gravel. Gravel increasing with depth.

Laterite caprock at 1.3m

Figure 4 Soil profile description and root distribution maps ($1m^2$) in reconstructed profile 4

4.2 pH and electrical conductivity

The reconstructed profiles had distinctly different pH and electrical conductivity (EC) profiles in the near-surface materials compared to the natural soils although this difference disappeared with depth (Figure 5). The EC of most materials sampled was low (Table1), with the bulk of soil horizons / layers considered to be non-saline (0-200 uS/cm) to slightly saline (200-400 uS/cm), based on the standard USDA and CSIRO scales. The EC of all profiles dropped sharply beyond the topsoil, with negligible salinity levels in all sub-surface soil horizons / reconstructed layers. Soil pH was acidic for all samples and with the profiles declined with depth to near pH 6 in all profiles. Surface soils had a more acidic pH in the natural profiles (near pH 5), whereas the reconstructed profiles were nearer pH 5.5.

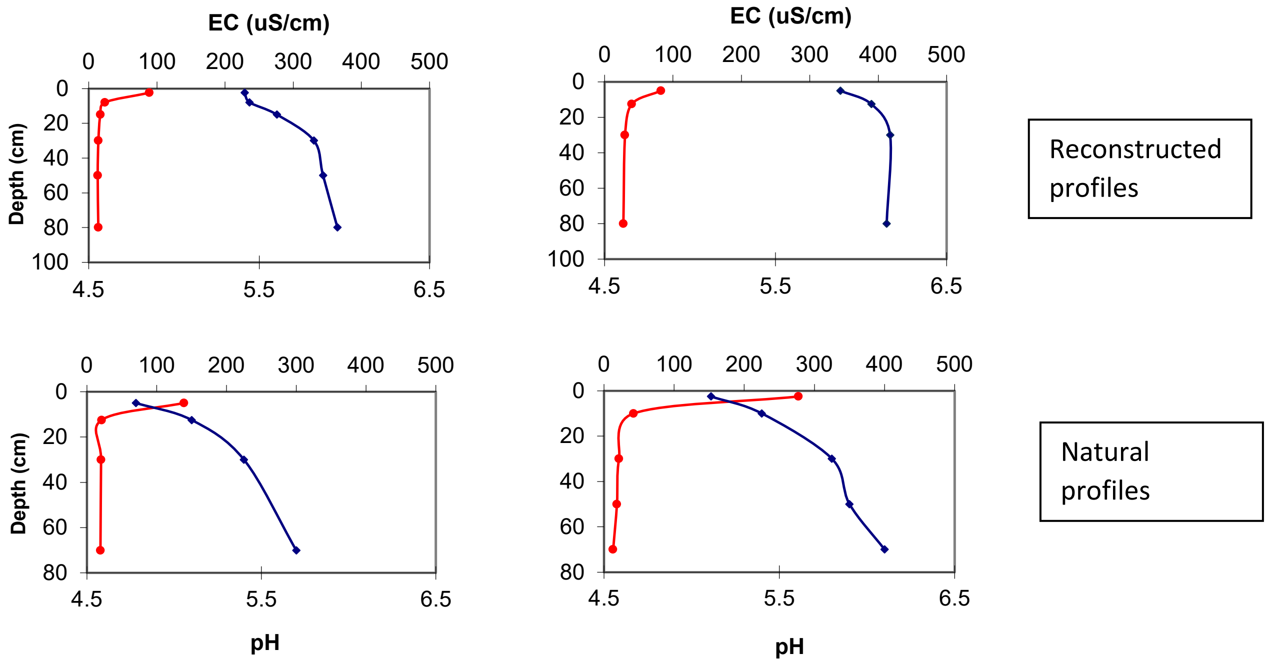


Figure 5 **Soil electrical conductivity and pH with depth in 2 reconstructed and 2 natural profiles, where —•— = EC and —◆— = pH**

4.3 Physical properties

Overall, there were some differences found in particle size distribution, for modulus of rupture (in subsoils only) with no differences in dry bulk density (Table 1). All materials were dominated by the coarse gravel fraction (>2 mm). The fine earth component (<2 mm) was predominately sand, with very small amounts of silt and clay. The topsoils from the mined and unmined areas differed significantly in their gravel, sand and silt percentages (Table 1). The dry bulk density of the soils varied slightly at ~1.1g/cm3 for topsoil and ~1.2g/cm3 for subsoils there were no significant differences between reconstructed and natural soils. Modulus of rupture showed significant differences in soil strength only in the subsoil.

Table 1 Soil physical characteristics for topsoil and subsoil materials from rehabilitated and unmined areas. Bolded values represent significant differences between rehabilitated and unmined soils at the $P < 0.05$ level. The number of replicate samples (n) for each parameter is shown in the statistic column

Characteristic	Measure	Statistic	Topsoil Rehabilitated	Topsoil Unmined	Subsoil Rehabilitated	Subsoil Unmined
Soil electrical conductivity (EC) and pH	**pHw (1:5)**	**Mean**	**6.07**	**5.64**	**6.49**	**6.16**
		S.E.	0.04	0.02	0.04	0.02
		n	90	54	126	72
	pH$_{CaCl2}$ (1:5)	**Mean**	**5.45**	**5.12**	**5.84**	**5.33**
		S.E.	0.02	0.03	0.02	0.04
		n	90	54	126	72
	EC (1:5) uS/cm	**Mean**	90	54	126	72
		S.E.	**184.86**	**320.95**	27.22	33.32
		n	13.08	26.98	0.82	1.73
Soil particle size analysis (%)	**Gravel**	**Mean**	**66.4**	**56.2**	**75.9**	**66.8**
		S.E.	0.6	2.8	1	0.9
		n	30	18	42	24
	Sand	**Mean**	**29.4**	**38.3**	**20.4**	**29.5**
		S.E.	0.7	3.7	0.7	0.8
		n	20	12	28	16
	Silt	**Mean**	**2.0**	**2.8**	1.7	1.9
		S.E.	0.1	0.4	0.2	0.3
		n	20	12	28	16
	Clay	**Mean**	2.2	2.7	2	1.8
		S.E.	0.1	0.4	0.5	0.3
		n	20	12	28	16
DBD and Modulus of Rupture	**Dry Bulk density (g/cm3)**	**Mean**	1.17	1.12	1.29	1.22
		S.E.	0.02	0.02	0.02	0.05
		n	8	5	7	2
	MOR (kPa)	**Mean**	0.12	0	**29.5**	**0**
		S.E.	0.12	0	0.62	0
		n	108	54	111	72

4.4 Chemical properties

The concentration of mineral N (NO_3^- and NH_4^+) and S was found to be significantly higher in the topsoil from the unmined areas than in the rehabilitated areas (Table 2). In particular, the concentration of nitrate-N was approximately double in the unmined area when compared to the rehabilitated area. The amount of Fe however was significantly lower in the unmined area. The subsoil in the unmined area also had significantly more N, P and K, but less S, than the subsoil in the rehabilitated areas. The CEC of the topsoil materials from both the rehabilitated and unmined areas was medium, while the subsoils had low CEC (Moore 2004). There was no significant difference in the CEC of the topsoil and subsoil materials from the mined and unmined areas. There was a significantly higher level of organic carbon in the topsoil from the unmined areas compared to the topsoils from the rehabilitated areas (Table 2).

Table 2 Soil chemical characteristics for topsoil and subsoil materials from rehabilitated and unmined areas. Bolded values represent significant differences between rehabilitated and unmined soils at the $P < 0.05$ level. The number of replicate samples (n) for each parameter is shown in the statistic column

Characteristic	Measure	Statistic	Topsoil Rehabilitated	Topsoil Unmined	Subsoil Rehabilitated	Subsoil Unmined
Available nutrients (mg/kg)	**NO_3^- N**	**Mean**	**42.00**	**88.60**	**2.29**	**6.78**
		S.E.	9.74	10.42	0.37	1.47
		n	13	5	14	9
	NH_4^+ N	**Mean**	**2.08**	**9.83**	1	1
		S.E.	0.31	1.96	0	0
		n	13	6	14	10
	P	**Mean**	53.69	70.17	**3.308**	**6.5**
		S.E.	9.38	13.12	0.38	1.26
		n	13	6	13	10
	K	**Mean**	181	137.6	**25.57**	**44.8**
		S.E.	27.28	18.723	2.95	8.45
		n	13	5	14	10
	S	**Mean**	**30.35**	**10.4**	**10.33**	**4.75**
		S.E.	7.56	2.46	1.69	0.56
		n	13	6	13	10
	Fe	**Mean**	**1035.23**	**603.33**	548.93	453.9
		S.E.	91.88	64.4	52.35	49.53
		n	13	6	14	10
Cation exchange capacity and organic carbon	**CEC**	**Mean**	7.93	9.58	2.85	2.97
		S.E.	0.49	1.48	0.19	0.55
		n	10	6	14	8
	Organic C (%)	**Mean**	**3.36**	**5.28**	0.54	0.97
		S.E.	0.28	0.58	0.08	0.22
		n	13	6	14	10

4.5 Pasture assessments

Mean species composition, the average plant numbers for each species, were similar in undisturbed and rehabilitated sites, with the greatest difference being the larger proportion of capeweed and lower clover numbers in the undisturbed pastures (Figure 6).

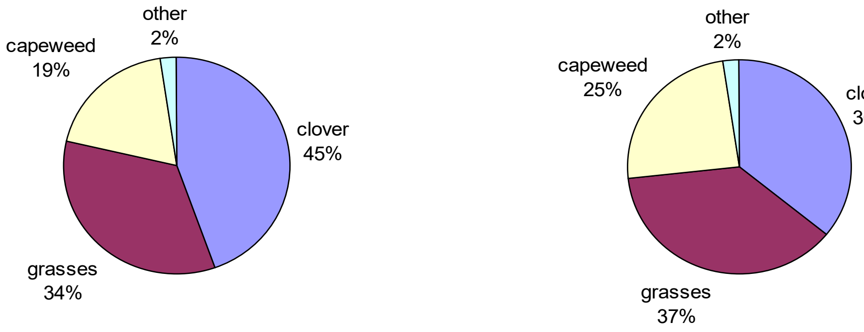


Figure 6 Mean pasture composition for rehabilitated and undisturbed pasture sites

Pasture dry matter production for the three sample dates exhibited a fluctuation in productivity at most sites throughout the growing season. There was a large variation in total pasture growth and the growth of individual species between sites at the time of each dry matter cut, with no consistent differences between the reconstructed and undisturbed sites. Early in the growing season dry matter yield was considerably lower in the rehabilitated sites, and whilst there were significant differences in the total dry matter production over the growing season between individual sites (data not shown), there was no consistent difference attributable to disturbance (Table 3).

Table 3 Mean dry matter yield for rehabilitated and undisturbed sites

Combined sites 9th July	Average dry matter (g/m^2)	Sig. Diff. 5%
Rehabilitated Sites	85.6	a
Undisturbed Sites	116.5	a
LSD 5%	**46.6**	

Combined sites 17th Sept	Average dry matter (g/m^2)	Sig. Diff. 5%
Rehabilitated Sites	150.2	a
Undisturbed Sites	151.4	a
LSD 5%	**97.0**	

5 Discussion

The unique opportunity of this study was to compare rehabilitated sites to adjacent undisturbed pastures in a number of fields that had been cut in half by mining activity. Unlike other studies (e.g., Bennett et al., 2021; Grigg et al. 2000) we were able to assess the effect of edaphic parameters and pasture productivity in sites that were disturbed (mined) and rehabilitated sequentially with undisturbed neighbouring sites. As there was substantial anecdotal evidence that pasture productivity was lower in rehabilitated sites, we aimed to understand the limitation to achieving comparable levels of soil fertility (physical and chemical soil properties) and pasture productivity to those of the pre-mined landscapes.

Assessment of pasture productivity showed little difference in yield and species composition in terms of statistically significant differences. However, the mean dry matter yield in the early austral growing season was almost one third less in the rehabilitated sites in this critical early phase. For rehabilitated and undisturbed sites, the pasture yield in the second half of the growing season was almost identical, suggesting reliable assessment protocols. Early season growth was not as consistent across sites and this introduced variability into the data as some sites had more rapid early season growth. It is notable that available nitrate and ammonium concentration in the soil was considerably, and significantly, lower in the rehabilitated soils despite common fertilisation and rhizobial inoculation regimens. This may have impacted pasture growth aboveground and belowground.

Soil pit descriptions show the profiles are unequivocally different despite the care to reconstruct equivalent horizons. This is not unexpected, and the rehabilitated sites are restored as well as might be expected. Three key physical parameters can be linked to explain some likely restriction to pasture production: (i) profile structural characteristics, (ii) root distributions, and (iii) modulus of rupture (MOR).

Soil structure describes the arrangement of solid particles and void space in a soil and is an important factor influencing the ability of soil to support plant growth, store and transmit water and resist erosion processes. A well-structured soil is one with a range of different sized aggregates, with component particles bound together to give a range of pore sizes facilitating root growth and the transfer of air and water. Soil structure can be influenced by the particle size distribution, chemical composition and organic matter content of a soil, and is often affected by root growth, stock and vehicle compaction, and with respect to reconstructed soil profiles, the methods of soil handling and deposition.

The undisturbed soil horizons and reconstructed layers can be classed as apedal as they have no aggregation of soil into peds. This is largely due to the low proportions of silt and clay sized particles within the soil. The <2mm fraction of these soils, classified texturally as sands to sandy loams, are generally single grained, as they separate readily into individual grains. Such soils, unless compacted, generally have adequate pore space to allow the movement of air, water and the growth of roots. The topsoils of most sites are predominantly apedal, single grained, although there is a degree of weak structure evident in some topsoils induced by root growth (i.e., soil bound together into aggregates by roots).

Root distributions were highly restricted in the reconstructed soil and not as deep as that of the undisturbed profiles. Root penetration in reconstructed profiles is delineated by the reconstructed layers indicating an impediment to growth in deeper layer. This may be a result of increased soil strength restricting root growth to the upper layers only, which in a seasonally arid climate may have a negative impact on pasture growth. MOR identifies the tendency of a soil to hardset as a result of slaking and dispersion and provides insight into the potential for layers to hardset and compact with repeated wetting and drying cycles, and the ability of roots to fracture the soil and penetrate crack faces. A MOR of over 60kPa has been described as the critical value for distinguishing problem soils (Cochrane and Aylmore 1997). Restricted root penetration into the soil matrix is a likely consequence of a high MOR. In reconstructed soil profiles, materials normally deep in the profile that may have a high MOR can often be redeposited closer to the surface leading to root penetration problems. Although all values were below the value of 60kPa, generally regarded as being problematic, it may still have been impactful for a new developing pasture system. Also, the unmined soil has higher levels of EC and organic carbon than the rehabilitated soils. It is possible that free salt could prevent dispersion and organic matter aid cohesion, impacting positively on structure in a manner lacking in the reconstructed profiles. In combination, poor structural development, elevated MOR and restricted root development may have combined to cause some physical barriers to pasture growth.

Published literature indicates that there are a range of ‘critical values’ for plant extractable nutrients in soils, below which reduced yields due to nutrient deficiencies may occur (Gourley 1999; Lewis 1999; Strong and Mason 1999). These critical values vary with soil type, rainfall and plant species however an approximate guide for the pastures where nitrate < 45 mg/kg, P < 25 mg/kg, K < 40 mg/kg and S < 10 mg/kg may be problematic. The mean plant extractable nutrient concentrations in the topsoils from both the mined and unmined areas exceeded all these critical values. Although the rehabilitated soils are unlikely to have achieved the significant stratification of nutrients found in the topsoil of regularly fertilised Australian pastures (Ryan et al. 2017), nutrient deficiencies may not have strongly affected rehabilitated pastures despite some difference between reconstructed soils and undisturbed profiles. The exception is likely to be nitrogen where the significant difference was quite stark and the contributing effectiveness of rhizobial inoculation has not been assessed. It seems likely that physical disturbance of the soil material may have had a diluting effect of some of the organic matter and nutrient rich topsoils (Tibbett 2010), and this may have contributed to a multifactorial set of agents that are in addition to the physical factors described above.

Soil organic carbon was significantly lower in the rehabilitated topsoil than the undisturbed pastures. This is an indication of incomplete soil development. As carbon is the primary source of energy for soil organisms this suggests that biological activity may be restricted, limiting biological functions (DeJong et al. 2015). The current study did not consider biological fertility and should be the focus of further work on this site.

In conclusion, no single physico-chemical constraint to pasture production on the rehabilitated land was identified. It seems likely multifactorial set of agents including the handling and mixing of the soil material causing impenetrable zones, lack of soil organic matter and the dilution of fertile topsoil may be the underlying cause of reduced pasture production.

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