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Insights and Lessons Learned From the Long-term Rehabilitation of an Iron ore Mine

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ABSTRACT:A long-term study was conducted between 1985 and 2003 on rehabilitation trials at Sishen Iron Ore Mine, South Africa, to identify grass species that would survive in the artificial growth medium applied to the sites, and to determine the most suitable medium for sustainable vegetation growth. Vegetation establishment was tested at slopes of 18° and 34° and with five different cover materials. After 17 years of rehabilitation, investigations showed that weathered limestone sloped at 18° produced the highest percentage of plant cover and least erosion. Sixteen grass species were introduced and identified in the survey, with *Eragrostis* sp. and *Cenchrus ciliaris* as the dominant species. In 2004, new trials were initiated at the same mine to evaluate the effectiveness of different seeding methods and supplementation of the growth medium with organic material. After 4 years, hydro seeding was found to be the best method to distribute seeds evenly and to ensure uniform vegetation growth. Different engineering designs, such as changing the contour length and slope, had little influence on the measured parameters. A total of 28 grass species were identified in the sampling plots, with *Enneapogon cenchroides* and *Cenchrus ciliaris* as the dominant ones. Dehydrogenase activity was used as a proxy for microbial activity, and a positive association was observed between microbial activity and percentage organic carbon, emphasising the importance of soil organic matter in the soil development process.

Key words: Enzymatic activity, Microbial community, Mining, Revegetation, Tailings

INTRODUCTION

South Africa is a country rich in natural resources and minerals, and the mining sector substantially contribute to the economy, both in terms of mined materials and providing employment. However, mining activities adversely affects the environment and surrounding communities (Milton, 2001; Mummey *et al.*, 2002). For example, open-cast mines, such as iron-ore mines, lead to the discharge of waste rock material on potential grazing lands. The rehabilitation of this coarse material is extremely difficult due to aridity, wind and nutrient-poor soils (Van Rensburg & Rossouw, 2008). Sishen mine is located near Kathu, approximately 200 km north-west of Kimberley in the Northern Cape Province. Climate data over a 52 year period shows an average annual rainfall of 455 mm for the area, mostly in the summer months (Weather Bureau, 1984; Kumba Resources, 2006). Sishen mine is the largest single-pit (uninterrupted) iron ore mine in the world and is known as a source of high-quality iron. The pit was established in 1953 and the total mine production since its establishment is estimated at 812 Mt, yielding approximately 665 Mt of saleable product. The disturbed expanse-area at the mine covers over 6193 ha.

The ultimate aim of rehabilitating sites disturbed by mining activities is to return a disturbed site to some resemblance of its former state, or to a sustainable usable condition. However, it is recognised that this rehabilitated condition will most probably not match the original condition and allow optimal land use of the impacted area (Mulligan, 2002). South African legislation imposes a clear obligation on mining companies to prevent environmental damage and defines specific responsibilities associated with mine closure and rehabilitation. According to the

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Minerals and Petroleum Resources Development Act (Act 28 of 2002) section 38 (1) (d), any person who is a holder of a reconnaissance permission, prospecting right, mining right, mining permit or retention permit must, as far as it is reasonably possible, rehabilitate the environment affected by the prospecting or mining operations to its natural or predetermined state or to a land use which conforms to the generally accepted principle of sustainable development. This review evaluates rehabilitation practices applied at the Sishen mine over 23 years and makes recommendations towards the best practices for rehabilitation in the studied context.

Soil formation and the establishment of vegetation cover are essential for achieving rehabilitation of disturbed areas (Carroll *et al.*, 2000). Adverse factors that can complicate the establishment of vegetation cover include a soil environment with poor physical characteristics, low levels of plant nutrients and organic matter, pH extremes and the presence of heavy metals. The elevated topography of tailings and mine stockpiles accompanied by climatic conditions characteristic of arid and semi-arid areas of southern Africa also deter the establishment of permanent self-sustaining vegetation cover (Milton, 2001). The interaction of re-vegetated plants with the physical, chemical and biological components of the soil environment, determine whether vegetation will persist on rehabilitated areas (Van Rensburg *et al.*, 2004). Therefore, it is important, when characterising soil quality, to use a selection of all types of soil properties representing soil quality as a whole. These should include properties that are relevant to the chemical, physical and biological aspects of soil that are most sensitive to management practices and environmental stress. Such a holistic approach is crucial to promote the sustainability of environments by providing accurate information on the status of the soil ecosystem as a whole (Ibekwe *et al.*, 2002).

The significance of microbial communities in sustainable soil ecosystems has been acknowledged for some time. Accordingly, soil microbial properties have often been proposed as timely and sensitive indicators of soil ecological stress or rehabilitation processes (Bandick & Dick, 1999; Badiane *et al.*, 2001; Ibekwe *et al.*, 2002; Tate & Rogers, 2002). The analysis of a variety of soil enzymes gives an indication of the diversity of functions that can be fulfilled by the microbial community (Brohon *et al.*, 2001). Enzymatic activities such as those of dehydrogenase, ß-glucosidase, urease, and phosphatase show significant correlation with total organic carbon, total nitrogen, water-filled pore space, and heterotrophic bacterial and fungal biomass (Aon & Colaneri, 2001). Dehydrogenase is present in all microorganisms (Dick, 1997) and dehydrogenase activity is regarded as an accurate measure of the microbial oxidative capacity of soil and therefore of viable microorganisms (Dick, 1994; Taylor *et al*., 2002). Dehydrogenase activity has previously been used to estimate the degree of recovery of degraded soils (Gil-Sotres *et al*., 2005). B-Glucosidase activity is useful in the monitoring of soil ecosystems for several reasons: it shows low seasonal variability (Knight & Dick, 2004), plays a central role in the cycling of organic matter, is the most abundant of the three enzymes involved in cellulose degradation, and is rarely substrate limited (Turner *et al*., 2002). Phosphomonoesterases are involved in organic phosphorus transformations in soil. They have low substrate specificity and are the predominant phosphatases in most soils. They are classified as acid phosphatases and alkaline phosphatases by virtue of the pH-optima of activity. Soil microorganisms produce alkaline phosphatases while acid phosphatases are mainly produced by plant roots (Criquet *et al*., 2004). Urease activity is often measured due to its importance in the nitrogen cycle, and it has been widely used to evaluate changes in soil quality due to soil management processes.

MATERIALS & METHODS

In order to address issues on the rehabilitation of mining waste in the semi-arid and arid areas of South Africa, long-term rehabilitation trials were conducted at the Sishen Iron Ore Mine in 1985. The aim of the original trial was to identify grass species that would survive in the artificial (non-topsoil) growth medium applied to the sites, and to determine the most suitable medium for sustainable vegetation growth over the long term (Van Wyk, 1994). Chemical analyses of a variety of potential cover materials available at Sishen in 1986 to serve as a growth medium is shown in Table 1. From these, nine different materials and mixtures were selected according to their nutrient status to evaluate the establishment of vegetation (Table 2)., A 0.5 m layer of banded ironstone followed by a 1 m layer of limestone was placed underneath the layer of topsoil and mixed materials, before reaching the iron ore discard. The final evaluation of the trials started in 1985 was concluded during 2008.

For the 1987-1990 trials, cover materials were selected according to results obtained from the level surface trials (Table 3).

Ten different treatments were applied to the sites (Table 4). Treatments consisted of a combination of rehabilitation practices and/or amendments applied to a specific site. First, the ‘engineering’ aspect was taken into account. A value of 1 indicates a 1 m contour

Table 1. Chemical analyses of the different materials available at Sishen Iron Ore mine

Material	pH		Available plant nutrients (ppm)					Texture			
	H2O	KCl	P	K	Ca	Mg	Na	Coarse	Fine	Silt	Clay
Lime	6.8	7.8	<3	33	3211	245	19	34	622	39	5
Red clay	6.4	7.4	<3	152	6310	1557	38	1	19	80	0
Lawa	6.7	8.2	<3	51	1822	124	22	70	28	1	1
Quartzite	6.8	7.9	<3	10	68	9	8	72	27	1	0
Tech shale	6.6	7.4	<3	37	646	346	33	1	23	50	26
Flagstone shale	5.9	6.7	<3	66	141	33	14	64	26	9	1
Black shale	5.7	6.3	<3	80	204	88	14	66	30	4	0
Brown shale	5.9	6.8	<3	173	152	32	10	76	21	2	1
Fine ore	5.9	6.8	<3	54	41	52	54	74	16	9	1
Silt	6.3	7.3	<3	112	1909	264	543	2	7	62	29
Discharge	6.7	7.8	<3	39	419	63	15	72	26	1	1
Diabase	7	8	<3	123	10371	1739	47	9	46	18	27
Red topsoil	5.2	6.7	<3	262	2681	1271	67	26	35	12	27
Dark topsoil	6.2	7.7	<3	343	3666	154	42	18	61	10	11

Table 2. Different materials and mixtures selected in 1986 for level-surface trails to evaluate potential cover materials

Plot	Material	Description
1	Fine limestone	-
2	Fine iron ore discard	-
3	50% fine limestone + 50% discard	Reduces the silt content of the limestone, improves infiltration and increases the nutrient status of the discard
4	70% limestone + 30% discard	Reduces the silt content of the limestone, improves infiltration and increases the nutrient status of the discard
5	70% limestone + 30% discard + 50mm red topsoil	This mixture consists of more fine material and microorganisms
6	90% limestone + 10% red topsoil	Improves texture and contributes fine material and microorganisms to the limestone
7	90% limestone + 10% dark topsoil	Improves texture and contributes fine material and microorganisms to the limestone
8	70% discard + 30% diabase	Improves texture and nutrient status of the discard
9	50% discard + 30% limestone + 20% diabase	Improves texture and nutrient status of the discard

Table 3. Different cover materials selected were fertilised according to chemical analysis

Material	2:3:2 (22)	Super phosphate	KCl	MgO
Un-weathered limestone	200	400	600	-
Weathered limestone	200	400	300	-
Sandy soils + stone	200	400	-	-
Fine iron ore discard + stone	200	400	200	100
Fine iron ore discard + stone + diabase	200	400	1000	-

Table 4. Different treatments applied to the sites at Sishen Iron Ore Mine in 2004

Treatment	Engineering	Hydro seed	Topsoil	Organic	Fertiliser
1	1	0	0	0	0
2	1	0	0	1	0
3	1	0	0	1	1
4	2	0	1	0	0
5	2	1	1	2	2
6	2	0	0	1	1
7	2	1	0	1	1
8	2	1	0	2	3
9	2	1	0	2	1
10	2	0	0	1	1

length and 2 indicates a 2 m contour length. This included sites that were physically altered during the rehabilitation process by creating contours at varying distances from one another. The second treatment aspect considered was whether hydro seeding or hand seeding was applied to a site. Thirdly, treatments either included the application of a topsoil layer or not. The last two columns of Table 5 show whether organic material and/or fertiliser were applied to the sites. The absence and presence of these treatment constituents are indicated by 0 (absence) or 1 (50 t/ha). A value of 2 indicates that double the amount was applied and a value of 3 that triple the amount was applied to the sites.

Plots for the 2004 trials were laid out on two terraces, three different slope angles were used in the investigation (Table 5).

RESULTS & DISCUSSION

The results of the vegetation properties (% basal cover) derived from the 1986–1990 slope trials are illustrated in Fig. 1. The irrigated 18 ° slopes had better grass cover than the non-irrigated 34 ° slopes. In most of the trials the basal cover percentage increased from 1988 to 1990 with *Cenchrus ciliaris* as the dominant grass species.

The 34 ° slopes remained mostly barren in 1990, with 60–80 % of the trial plots non-vegetated. On the level-surface trials it was found that fine iron ore discard, topsoil and a mixture of 70 % discard and 30 % diabase, produced the best initial results for revegetation with *Eragrostis achinochloidea* and *Cenchrus ciliaris* being the dominant grass species. The 90 % limestone and 10 % dark topsoil produced the poorest results with 63.3 % bare ground in the trial plots. Results obtained in 2003 from the 1985 trial plots indicated that there was a difference in the dehydrogenase activity for the various treatments after 17 years of rehabilitation with 50 % diabase, 50 % discard, and irrigation outperforming the other treatments in terms of vegetation establishment and microbial activity. Multivariate ordination methods can be used to determine how community composition varies with environmental variables, using correlation

Table 5. Site layout with different treatments as identified in November 2004

Upper Slope																
Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T1	T2	T3	T10		
Slope angle (°)	24	24	24	24	24	24	24	24	24	24	34	34	34	34		
Lower slope																
Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T4	T5	T6	T7	T8	T9
Slope angle (°)	18	18	18	18	18	18	18	18	18	18	34	34	34	34	34	34

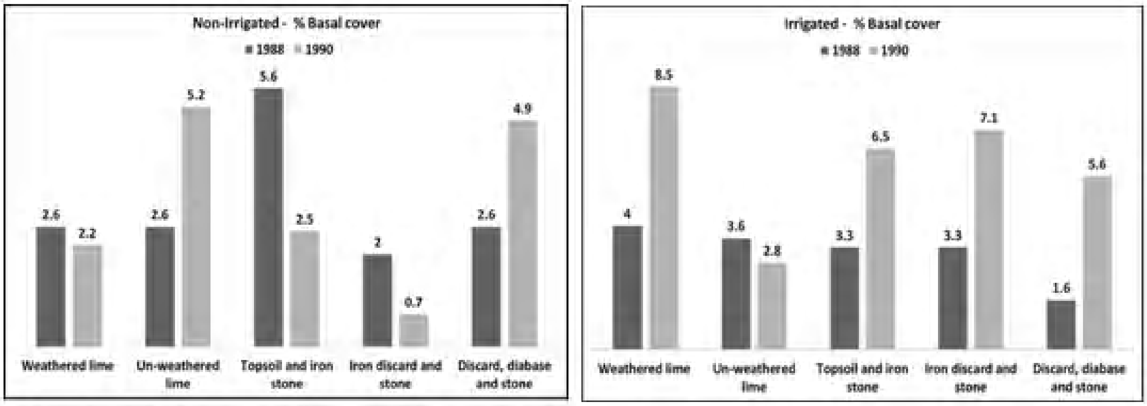

Fig. 1. Bar graphs indicating percentage basal cover for sites not irrigated in 1988 and 1990; and percentage basal cover for sites irrigated in 1988 and 1990

coefficients to analyse the data (Lepš & Šmilauer, 2003). Principal components analysis (PCA) ordination consists of two variables that are ordinated together (bi-plots), whereas canonical correspondence analysis (CCA) ordinations consist of three variables that are ordinated for comparison (tri-plots). Ordination diagrams can consist of points representing species and sampling sites, and vectors for quantitative environmental variables. Each species point in the diagram is positioned to represent the average of the sampling site points in which it occurs. Individual vectors represent the quantitative value for each environmental variable. The length of each vector indicates the gradient of the variables with the ordination axes. Dissimilarities are associated with the distance between the samples; the closer samples are to each other or to a vector, the higher the similarity between them. The linear correlation coefficients can be indicated by the angles between the vectors. Vectors pointing in the same direction have a large positive correlation, whereas vectors pointing in opposite directions indicate large negative correlations. The axes of an ordination diagram distinguish between different ecological gradients within the samples (Ter Braak & Verdonschot, 1995).

Results from the 2007 survey are illustrated in the PCA (Fig. 2) of the relationship between the different enzymatic activities and the different treatments applied since 2004 (Table 1). The 18 ° (A) sites grouped together in the lower part of the ordination together with urease and acid phosphatase activity. The 24 ° (B) sites grouped together in the top part of the ordination and was associated with ß-glucosidase. The 34 ° sites (C) were spread across the top part of the ordination and sites C5 and C6 mostly associated with alkaline phosphatase and dehydrogenase activity.

Results from the 2008 survey are illustrated in the CCA (Fig. 3) of the relationship between grass species and the different treatments of the sites. Grass species grouped together with the slopes on which it established successfully. Sites treated similarly also grouped together in the diagram. There was a difference in the dehydrogenase activity for the 10 various treatments applied to the different sites. Treatment 5 performed the best, with the addition of topsoil, organic matter and fertiliser producing the highest dehydrogenase activity.

Over the period that the rehabilitation trials were conducted, *Cenchrus ciliaris* was the dominant grass species. In the microbial assays of both 2004 and 2008, treatment 5 (engineered with contours, with the addition of topsoil, fertiliser, organic material and hydro seeded) had the highest dehydrogenase activity with the addition of topsoil, organic matter and fertiliser indicating that these sites were the most successful. The number of grass species found in the survey of 2008 was high, indicating that other species were moving in from the surrounding environment. Fourteen species were seeded in 2004 and 28 species were identified in the survey after 4 years. Topsoil is the preferable treatment for establishment of vegetation and increased microbial activity (Claassens *et al.*, 2011). However, topsoil is particularly costly and difficult to obtain and the extensive surface area of this mine makes the application of topsoil as a standard rehabilitation practice for mine closure highly unfeasible. To establish the most effective and efficient way to stabilise and vegetate the slopes of the waste dumps, the mine authorities researched and tested different combinations of soil, slope and vegetation to improve the aesthetics of the pit and to prepare for mine closure in the long term. An overview of rehabilitation practices and outcomes for 23 years is presented in Table 6.

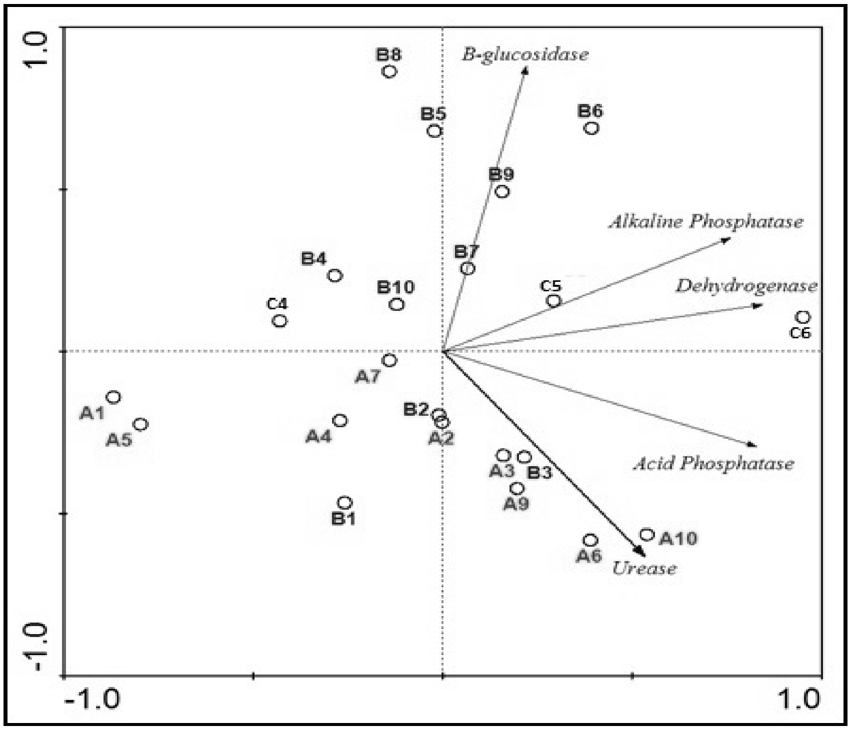

Fig. 2. Principal component analysis ordination diagram illustrating the relationship between microbial enzymatic activities and the different treatments in 2008

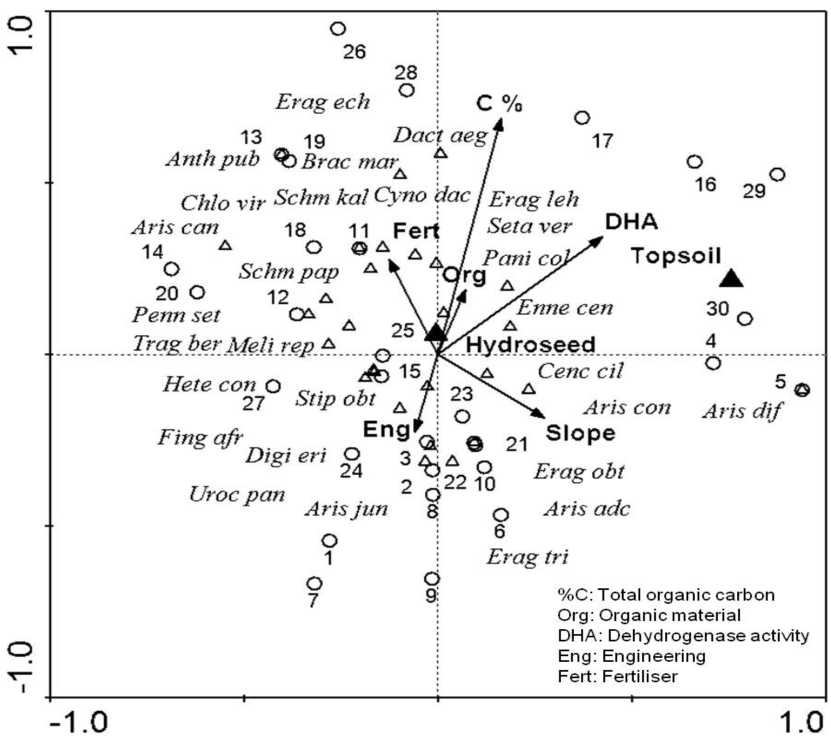

Fig. 3. Canonical correspondence analysis ordination diagram illustrating the relationship between grass species and different treatments of sites. Eigenvalues for the first two axes were 0.136 and 0.071, respectively

Table 6. Overview of rehabilitation practices and outcomes at Sishen Iron Ore mine

Time period	Methods	Seed mixture	Slope	Aim	Main conclusions and outcomes
1985	Three waste rock plots using different cover materials: Lime material, red Kalahari sand and untreated iron overburden		Natural angle of repose (34 °)	Identify grass species that would survive in the artificial (non-topsoil) growth medium.	Kalahari sand was the best material but eroded against the steep slopes. Alternative material needed to be tested but at lower slopes because Kalahari sand erosion was too high and limestone was not sustainable for vegetation establishment (Van Wyk, 2002).
1986-1990	Chemical analysis of a variety of potential cover materials available on the mine (Table 1) to serve as a growth medium.	*Cenchrus ciliaris, Enneapogon cenchroides, Eragrostis echinochloidea, Chloris virgata, Tragus berteronianus, Aristida congesta, Aristida adscensionis, Schmidtia pappophoroides, Schmidtia kalihariensis, Stipagrostis uniplumis, Stipagrostis obtuse, Melinis repens*	Level surface	Evaluate potential cover materials to assist in the establishment of vegetation.	Grass species found in all of the plots included: *Enneapogon cenchroides, Chloris virgata, Eragrostis achinochloidea, Cenchrus ciliaris*. *Salsola kali* was the dominant weed. The grass cover in the level surface trials were dominated by *Eragrostis echinochloidea* and *Cenchrus ciliaris* (Van Wyk, 2002). Fine iron ore discard, topsoil, and a mixture of 70% discard and 30% diabase, produced the best initial results for revegetation. The conclusion reached, was that the use of topsoil was ineffective and discard could be used as a cover material on level surfaces as it achieved the same results and was more cost-effective. The seed mixture should be adapted to include more species from the immediate vicinity of the mine (Van Wyk, 2002).
	Nine different materials and mixtures were selected according to their availability and nutrient status (Table 2) and were applied as cover layers of 20 – 30 cm on the surfaces of the trial plots.				
	Plots were fertilised and seeded in January 1986				
	Plots were fertilised with:				
	Vegetation establishment was compared with 5 different cover materials applied 150 – 200 mm thick (Van Wyk, 2002).	*Cenchrus ciliaris, Cynodon dactylon, Anthephora pubescens, Aristida congesta, Aristida adscensionis, Eragrostis lehmanniana, Eragrostis echinochloidea, Enneapogon cenchroides, Chloris virgata, Stipagrostis uniplumis, Stipagrostis ciliata, Stipagrostis obtusa, Tragus berteronianus, Fingerhutia africana, Urochloa brachyura, Schmidtia pappophoroides*		Use of different cover materials to determine the most effective against slope angles	1988: 18 ° slopes had better grass crown cover than the 34 ° slope and irrigated slopes had better grass establishment than non-irrigated slopes. 1990: the basal cover on the irrigated 18 ° slopes treated with un-weathered lime remained constant at 2.6%. In most of the other plots the basal cover increased from 2 to 4% in 1988 and from 4 to 8.5% in 1990. In all of the plots *Cenchrus ciliaris* was the dominant grass in 1990. The 34 ° slopes remained barren in 1990 and 60 – 80% was non-vegetated. In many of the plots the upper and lower third of the slope was eroded. The 34 ° slope covered with diabase and stone experienced the least erosion, although the vegetation cover was sparse. Most of the plots were dominated by the weed *Salsola kali*. Species dominating the grass cover were *Enneapogon cenchroides, Cynodon dactylon, Cenchrus ciliaris* and *Anthephora pubescens* (Table 2) (Van Wyk, 2002).

	Two sets of plots were laid out, the first consisted of 10 plots, five 18 ° and five 34 °. The second set of plots was identical to the first except that it was irrigated during the dry season (Van Wyk, 2002).			A replicate of each trial irrigated to determine the vegetation cover if the trial on the slopes without irrigation was not successful.	
Methods used for vegetation survey in 1986-1990 on level and slope trials					
Crown cover of individual species as well as total crown cover were determined by placing 0.5 m² survey circles randomly in each plot. Braun-Blanquet scale was used to determine crown cover values.					
Dry mass was determined using survey circles and cutting the vegetation within the circles. The material recovered was dried at 75 °C and weighed.					
Since 1990 the MONITOR-program of the Department Plant and Soil Science of Potchefstroom University was used for vegetation surveys. With this program basal cover and species frequency was determined (Van Wyk, 1994).					
2003	In 2003, the plots of 1987 were assessed for the last time by means of vegetation surveys and the analysis of soil microbial activity by means of enzymatic activity. Soil enzymatic activities were assayed according to standard procedures (Alef and Nannipieri, 1995). Assays are based on the incubation of soil with a specific substrate, followed by the colorimetric estimation of the reaction product. All enzymatic activities were determined using air-dried soil, except dehydrogenase, where soil was kept at field-water content.		18 ° and 34 °		After 17 years of rehabilitation, weathered fine limestone and fine discard applied as growth medium produced the best plant cover. These results also indicated that weathered limestone set at 18 ° produced the highest percentage of plant cover and less erosion than the slopes at 34 ° (Van Rensburg *et al*., 2004). Results obtained from the sampling of the 1987 trial sites indicated the presence of microbial activity in the artificial (non-topsoil) growth medium. There was no significant difference between the two different slopes based on enzymatic activity.
The results did not address other issues of rehabilitation such as the application of inorganic fertiliser to aid plant growth or the problem of lack of water-holding capacity of the growth medium. New studies were initiated to evaluate the effectiveness of different seeding methods and the effect of the addition of organic material to the growth medium.					

2004	Plots were laid out on two terraces of an east-facing slope, with 15 plots on the bottom slope and 13 plots on the upper slope. Three different slope angles were used in the investigation (Table 4). Ten different treatments were applied to sites on the bottom and the upper slopes (Table 5). Treatments consisted of a combination of rehabilitation practices and/or amendments applied to a specific site. Sites were monitored using vegetation surveys. The ground and crown cover at all the sites were estimated in three 1 m^2 quadrates randomly placed over a 50 m transect (Van Rensburg *et al*., 2004).	*Anthephora pubescens, Aristida adscensionis, Aristida congesta, Cenchrus ciliaris, Chloris virgata, Cynodon dactylon, Digitaria eriantha, Eragrostis lehmanniana, Eragrostis tef, Fingerhuthia africana, Heteropogon contortus, Schmidtia pappophoroides, and Tragus berteronianus*	18 °, 24 ° and 34 °	Evaluation of different seeding methods and application of organic material	The vegetation survey indicated that the treatments on the 24 ° slope performed the best and was less eroded than the 30 ° slopes. Areas that were hydro seeded out-performed hand sown areas and were characterised by a higher species frequency. Areas with topsoil and treated with a higher application rate of organic material generally performed better than treatments with lower organic treatment. Different engineering designs did not have a measurable influence on the vegetation composition and cover in the treatments. *Salsola kali* was the dominant invader species in the experimental plots and *Eragrostis sp.* and *Cenchrus ciliaris* were the dominant grass species (Van Rensburg *et al*., 2004). The texture of the material differed noticeably between the 18 ° and 24 ° slope treatments, which had a visible effect on seedlings. Seedling survival was therefore a potential problem especially for particular species such as *Heteropogon contortus*.
2006	Vegetation survey – Visual observations after good downpours of rain during early January 2006 (75 mm) on the 2004 sites (Van Wyk, 2006).		18 °, 24 °and 34 °	Evaluate vegetation establishment on the different treatments and slopes after two growing seasons.	From the results of the vegetation survey in 2006, it was clear that the addition of topsoil played an important role as a seed source, and it must be conserved during the mining process for rehabilitation. Conclusions reached during this study indicated *Cenchrus ciliaris* to be the dominant grass species, while *Heteropogon contortus*, *Digitaria eriantha*, *Anthephora pubescens* and *Fingerhuthia africana* were perennial grasses that could play an important role in the rehabilitation process. *Melinis repens*, *Enneapogon cenchroides* and *Aristida adscensiones* are annual species that were performing well (van Wyk, 2006). Contour furrows played an important role on both the 18 ° and 24 ° slopes because it created a favourable environment for the establishment of vegetation that served as a seed source for the downward slope. It was also concluded that amelioration is important in the establishment of healthy vegetation. With an increase in perennial grasses, there was a decline in the frequency of *Salsola kali* (van Wyk, 2006).

2007	Evaluate soil enzymatic activities: Dehydrogenase, β-glucosidase, alkaline and acid phosphatase and urease (Alef & Nannipieri, 1995). Statistical analyses were performed using Canoco for Windows 4.5 (Biometris – Plant Research International, Wageningen, The Netherlands) (Ter Braak *et al.*, 1998) to investigate the relationship between the different enzymes and site treatments using a principal component analysis (PCA) multivariate ordination technique.		18 °, 24 ° and 34 °	Evaluate the different treatments using soil enzymatic activities as assessment criteria on the different slopes.	The results show that the majority of the treatments applied to the sites on the 24 ° slope had a higher correlation with β-glucosidase and dehydrogenase activities, irrespective of the treatments applied (Figure 2). Furthermore, sites on the 30° slope treated with topsoil, organic matter and fertiliser also showed higher β-glucosidase and dehydrogenase activities, which might contribute to a faster recovery of iron ore overburden. [4] Treatments applied to the 18 ° slopes indicated a stronger association with urease and acid phosphatase activity. Acid phosphatase activity is an important source of plant roots and it was anticipated that an 18° slope is more suitable for the establishment of vegetation. However the treatment applications on the 24 ° slope can be considered to be more stable over the long term due to a stronger correlation of enzymatic activities that indicated higher microbial activity (Van Rensburg & Roussow, 2008).
2008	Sites were monitored using vegetation surveys and soil enzymatic activities (Alef & Nannipieri, 1995). The ground and crown cover of all the sites were estimated in three 1 m² quadrates randomly placed over a 50 m transect.[7] Total organic carbon was determined according to the Walkley-Black procedure (Walkley & Black, 1934). Statistical analyses were performed to investigate the relationship between the different enzymes and site treatments using a canonical correspondence analysis (CCA) (Canoco for Windows 4.5) multivariate ordination technique.		18 °, 24 ° and 34 °	Evaluate the different treatments using soil enzymatic activities and vegetation cover as assessment criteria on the different slopes	After four years of rehabilitation on the new trials, it was found that different engineering designs, i.e. slope length and slope, did not have a significant influence on vegetation composition and species diversity. Growth medium was not homogeneously applied over the sites, and thus led to a variety of materials found from the bottom of the slope to the top. Sites with no or little addition of organic matter and fertiliser showed a correspondingly low enzymatic activity because of the rocky material. Treatment 5 had the highest dehydrogenase activity, due to the addition of topsoil, organic matter and fertiliser (Figure 3). *Cenchrus ciliaris*, *Enneapogon cenchroides* and *Heteropogon contortus* were the most dominant grass species in all sites (Figure 3).

CONCLUSION

The main conclusion reached about the rehabilitation at the Sishen mine was that the addition of topsoil together with organic matter and fertiliser contributed to the fastest recovery of iron ore overburden and achieved the most success in terms of vegetation establishment. It was also clear that different engineering designs did not have a measurable influence on the vegetation composition and cover at the different sites, hence that this factor can be disregarded in the rehabilitation plan for mine closure. Further studies are desirable to evaluate the progress of the sites in terms of the development of organic matter and biodiversity. The following insights were gained from the different management practices applied at the mine:

- Vegetation can be established at a 24 ° slope angle on the north- and east-facing slopes. On the western and southern slopes, successful vegetation establishment would be possible at a 34 ° slope angle if the practical limitations of reshaping for surface water control can be overcome.
- To achieve vegetation success, the application of organic matter is vital to increase the water-holding capacity, as well as the microbial activity of the growth medium. The importance of the soil carbon fraction in rehabilitated soils is one of the most undervalued components of rehabilitation. From the trials conducted at Sishen, it is clear that one of the main limitations of tailings materials in terms of vegetation sustainability is the lack of organic matter in the growth medium profile. Sites treated with compost had significantly higher biodiversity and it was found that root development, above-ground biomass production, and therefore the basal and crown cover outperformed areas without compost.
- Hydro seeding is the best method for seeding despite the arid climate at Sishen. This method distributes the seeds evenly and results in a more uniform vegetation cover.
- A seed mixture containing the following grass species proved to be the most successful – *Cenchrus ciliaris* became the dominating grass species, whereas *Heteropogon contortus, Digitaria eriantha, Anthephora pubescens* and *Fingerhuthia africana* are perennial grasses that play an important role in successful rehabilitation. *Melinis repens, Enneapogon cenchroides* and *Aristida adscensiones* are annual species that were found to perform well (Van Rensburg & Roussow, 2008).
- Topsoil application is not essential but a fine material cover layer that can be shaped for surface water control is required. Topsoil tends to erode notably and should only be used in high priority areas as it is expensive to apply.
- Surface water flow needs to be well managed and banks should be back-sloped as this has often been the main reason for erosion in the past.

Sishen mine is taking a step in the right direction by acknowledging their responsibility toward the environment and future generations seriously through assessing rehabilitation practices and determining what is best for the mine. Significant contributions made by this review include the identification of parameters essential for rehabilitation success at Sishen mine and the establishment of an overview of the history of rehabilitation practices applied at the mine.

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