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Pastures established on rehabilitated surface coal mined land: an assessment of forage production and implications for livestock grazing

Emmanuel Nkosinathi Cele[1, 2*], Monde Rapiya[1], Wayne Sanders[1], Wayne Truter[3,4]

[1] *Department of Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa*
[2] *Department of Environmental Health Science, University of Eswatini, Mbabane, Eswatini*
[3] *Enterprises University of Pretoria, Pretoria, South Africa*
[4] *Green Futures Hub, Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, South Africa*
**Correspondence: cele.en2025@gmail.com*

Currently, land rehabilitation best practice in South Africa is to revegetate ameliorated soil with grass mixtures. These grasses have valuable grazing potential that can deliver great benefits to livestock farmers. However, due to paucity of research and published findings, the viability of such post-mining land use in South Africa remains unclear. To evaluate the grazing potential of rehabilitated mine lands, this study examined soil properties, biomass, and veld condition across a 4–30-year chronosequence. Despite suboptimal pH in the majority of sites, there were satisfactory levels of Na, K, Ca and Mg. There was biomass production in all sites with high levels of basal cover (36–91%). Percentage veld condition scores were moderate (40–60%) to excellent (60–100%) in all sites. Decreaser species were the most abundant and the grazing capacity in all sites was 2.7–3.6 ha LSU^{-1}. These results were indicative of the ability of rehabilitated sites to withstand the impacts of soil erosion, with high potential to meet forage requirements of animals in terms of quantity. Based on these results, the implementation of controlled cattle grazing on rehabilitated mine lands in Mpumalanga, South Africa, appears to be a practicable post-mining land use option.

Keywords: basal cover, biomass production, grazing capacity, physicochemical conditions, rehabilitated surface coal mined land, veld condition

Introduction

South Africa has a mature mining industry, dating back to the 1860s with the discovery of diamond and gold deposits (Cornelissen et al. 2019). However, according to the Department of Mineral Resources and Energy (DMRE) (2022), mines were often abandoned after the production phase without considering any potential risks to humans and the environment or social dimensions. According to recent estimates, the number of abandoned mines in South Africa was said to be 5 906 at the end of May 2008. In 2019, it was thought that the country would need about R30 billion (Cornelissen et al. 2019) to R49 billion (Gilliland 2019; DMRE 2022) to rehabilitate these mines. Consequently, local communities in post-mining areas have traditionally faced a number of challenges including degraded landscapes, lowered environmental quality (Kivinen 2017) and notable declines in arable production and livestock farming due to loss of ploughing fields, grazing land and other natural resources (Mnwana and Bowman 2022). Losing the ability to derive land-based benefits can increase the vulnerability of local communities and have devastating effects on their well-being and resilience (Shackleton 2020).

In order to address mining problems of the past, current South African laws impose a clear obligation on mining companies to prevent environmental damage. Specifically, these are the Constitution (Act 108, 1996), the Mineral and Petroleum Resources Development Act (MPRDA) (Act 28, 2002) and the National Environmental Management Act (NEMA) (Act 107, 1998) (Chamber of Mines of South Africa and Coaltech 2007). Since the promulgation and implementation of the above-stated pieces of legislation, there have been a number of positive developments in mined land rehabilitation. For instance, one of the earliest positive steps was the development of clear guidelines for the rehabilitation of mined land in 2007 (revised in 2018) (Coaltech at al. 2019). Also, a national strategy for the management of abandoned mines in South Africa has been developed and several government-funded programmes are underway to address the myriad legacies of past mining activities (Cornelissen et al. 2019). Presently, the DMRE receives about R140 million per annum for the rehabilitation of mines (DMRE 2022), and about R120 million is spent on rehabilitation annually (Gilliland 2019). Based on these efforts, it was recently reported that about 0.7% of the abandoned mines mentioned above have been rehabilitated, with a further 3.2% classified as high priority for rehabilitation (Department of Forestry, Fisheries and the Environment 2017).

Currently, the land rehabilitation best practice in South Africa is to predominantly revegetate (seed) ameliorated soil of wilderness, pasture and arable land capability classes, with pasture grass mixtures. For the majority of South African situations, appropriate commercially available seed mixes have been developed for various climatic and soil combinations and these have proved effective in generating a rapid erosion-controlling cover that is sustainable under normal management conditions. For instance, *Eragrostis teff* is an annual pioneer grass that emerges very quickly to serve as a ground cover. On the other hand, while *Chloris gayana* provides good cover for up to four seasons only, *Cynodon dactylon* is a very effective ground stabiliser because it is a perennial creeping pioneer grass. Therefore, when the performance of one species declines, others persist, thereby avoiding the need for unnecessary re-seeding (Coaltech et al. 2019).

With regard to relevance to grazing, *C. dactylon* is extremely drought-tolerant (Mau-Crimmins 2007), and has a high grazing value, with about 12% crude protein content (Wang et al. 2009). *Chloris gayana* also has a high grazing value and is tolerant to heat, soil salinity, drought and flooding (Jamil et al. 2024). *Eragrostis teff* is fast growing and leafy (Ritz et al. 2020), and its chief value as a hay crop lies in its palatability, high nutritive value, narrow albumin ratio (for a grass hay), high yield, rapid growth, drought resistance and ability to smother weeds (Ketema 1997). Clearly, the revegetation of mined land with these (and other) species can deliver great benefits to both small and large community livestock farmers.

Currently, there is a pressing need to utilise rehabilitated land for agricultural purposes (arable production and/or livestock farming). It is well known that land area suitable for agricultural production in South Africa is limited (Truter 2007). Specifically, less than 14% of South Africa's total land is suitable for dry land cropping with only about 3% regarded as high-potential arable land (Simpson et al. 2019). However, despite such acute agricultural land scarcity, mining often occurs on land with high agricultural potential (Chamber of Mines of South Africa and Coaltech 2007), as is the case in the Mpumalanga region, which contains 46.4% of the nation's arable land (Simpson et al. 2019). Further, while coal mining continues to diminish the remaining agricultural resource base, the South African population continues to grow in tandem with increasing mining activities (Minerals Council 2021; Statistics South Africa 2021).

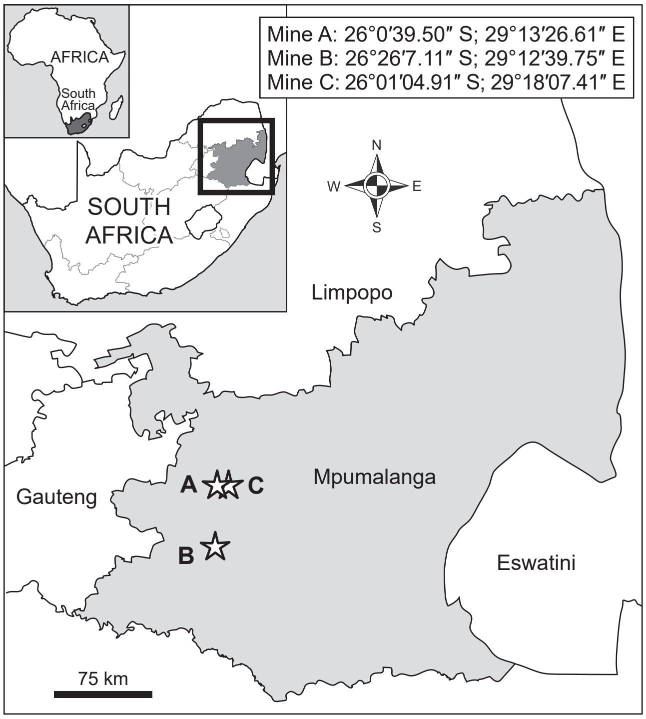

Figure 1: Location of surface coal mines (A, B and C) in Mpumalanga, South Africa, within which rehabilitated sites were chosen for the study

Based on the above, returning rehabilitated land to arable production and/or livestock farming is necessary to increase the country's ability to meet its food requirements. However, with regard to livestock farming, the viability of grazing as a post-mining land use in South Africa remains unclear due to the scarcity of research and published findings. Therefore, this study sought to investigate the potential of rehabilitated surface coal mined land in the Mpumalanga province to support cattle grazing. Specifically, the study aimed to assess (i) the current status of soil physicochemical parameters and (ii) seasonal variations in biomass production, basal cover, percentage veld condition, ecological status and grazing capacity.

Methodology

Selection and location of mines

Three surface coal mines, hereafter referred to as mine A, mine B and mine C, were selected in the Mpumalanga province of South Africa, the specific locations of which are shown in Figure 1.

Mine A

Study sites

Three differently aged, rehabilitated sites within mine A were selected. The site ages (i.e. the number of years after rehabilitation) were 7, 15 and 30 years. In the rest of this paper, these are referred to as A (7), A (15) and A (30), respectively. In the presentation of results, 'older sites/oldest sites' refers to sites that have been rehabilitated for many years, while 'younger sites/youngest sites' refers to those with the fewest years post rehabilitation.

Topography and climate

The mine lies on gently undulating terrain with elevations ranging from 1 498 to 1 590 m a.s.l.). Previously, natural surface run-off drained into marshy pans and non-perennial tributaries that ultimately drained into either the Tweefonteinspruit or the Olifants river. Regional climate is typical of the Highveld, with warm summers and cold winters. Mean minimum and maximum daily temperatures are 15 °C and 27 °C (respectively) in January and 2 °C and 18 °C (respectively) in July. Frost normally occurs between May and August. Mean annual rainfall is estimated at 696 mm and is mainly received between October and March. Hailstorms occur between October and December. Gusty winds usually occur between August and September (SRK Consulting 2012; Digby Wells Environmental 2014).

Geology and soils

The mine is situated in the Central Block of the Springs-Witbank Coalfield. The lithologies of the coalfield are Permian and Triassic Age segments of the Dwyka and Vryheid Formations of the coal-bearing Ecca Group of the Karoo. According to pre-mining assessments, the mine area consisted of major soils with high agricultural potential, such as Avalon,

Table 1: Pre-mining land capability of mine A

Block	Pre-mining land capability (%)			
	Arable	Grazing	Wetlands	Wilderness
2A	82.5	15.9	1.4	0.2
3AE	59	20	5.7	
3A North	72.7	11.7	4.4	11.2
3AW	37	46		5
4E	90	2.5		7.4
5W	28.7	62	2.9	5.9
5W Extension	23	23	10	
Discard area	87		13	

Source: SRK Consulting (2012)

Hutton, Glencoe, Mispah, Clovelly and Wasbank soil types (SRK Consulting 2012; Digby Wells Environmental 2014).

Pre-mining vegetation types

Past agricultural activity left very little of the original natural vegetation. Dominant grasses in this area were *Tristachya leucothrix*, *Eragrostis racemosa* and *Heteropogon contortus*. On land disturbed by previous mining, dominant secondary climax grass species were *Eragrostis curvula* and *Cynodon dactylon*. Most of the unmined lands consisted of *Eragrostis tricholaenoides*, *Andropogon schirensis* and *Cynodon dactylon*. Indigenous invader *Stoebe vulgaris* was a common component of the veld vegetation at the mine site. Exotic invader species included three species of wattle (*Acacia decurrens*, *A. dealbata* and *A. mearnsii*), the wild tomato *Solanum silymbrifolium*, kakiebos (*Tagetes minuta*), red river gum (*Eucalyptus camaldulensis*), blackjack (*Bidens pilosa*), Scottish thistle (*Cirsium vulgare*), Mexican poppy (*Argemone Mexicana*) and poplar species (*Populus canescens*, *P. deltoids*, *P. nigra*) (SRK Consulting 2012).

Pre-mining land capability and land use

The mine area is divided into eight blocks, covering an area of about 4 025 ha. The main pre-mining land capability classes for each of these blocks are shown in Table 1. The mine area was used for maize (3.0–4.5 tons per hectare) and cattle (3.1–6 stock units) farming. Some of the areas used for grazing were overutilised (evidenced by the appearance of bankrotbos (*Stoebe vulgaris*), while others were underutilised. Grazing land was predominantly grazed by livestock belonging to labourers who lived adjacent to the mining area. There were a number of existing structures (coal processing plant, offices, a sewage plant, workshops, water reticulation pipelines, overhead power lines and service roads, etc.) linked to previous (late 1970s – early 1980s) mining activities (SRK Consulting 2012).

Mine B

Study sites

Three differently aged, rehabilitated sites within mine B were selected. These were B (4), B (6) and B (9).

Topography and climate

The mine spans an elevation range of approximately 1 532–1 596 m a.s.l.. The local topography is flat to generally undulating. The area falls within a summer rainfall region, with generally low rainfall (averaging < 40 mm) from April to September and the highest rainfall (averaging > 60 mm) occurring from November to January. The mean annual rainfall is approximately 870 mm (Delta-H 2024), with incidence of frost ranging from 13 to 42 days per year during winter (The Biodiversity Company 2024a). In summer, temperatures range from 10 to 40 °C. Winters are milder and temperatures usually vary between 2 and 20 °C. The strongest winds blow from the southwest and northwest in winter and from the east and northwest in summer (WSP Environmental 2012).

Table 2: Pre-mining land capability of mine B

Land capability class	Area	
	(ha)	(%)
Arable	1 388.0	23.64
Grazing	1 662.2	28.31
Wilderness	1 284.1	21.87
Wetlands	1 537.1	26.18

Source: Groundwater Consulting Services (2000)

Geology and soils

The mine is located within the Vryheid Formation of the Ecca Group, part of the Karoo Supergroup. The Vryheid Formation is rich in sandstone and coal, and is stratigraphically transitional between the overlying Volkrust and underlying Pietermaritzburg Formations, both argillaceous in nature. The region's geology includes sandstone, shale, coal beds and dolerite dykes, alongside alluvium and aeolian sands (Eco Elements 2024). According to Groundwater Consulting Services (2000), there are about 21 representative soil forms that were identified within the mine area, and these include Avalon, Bainsvlei, Pinedene, Griffin, Clovelly, Hutton, Westleigh, Glencoe, Kroonstad, Rensburg, Katspruit, Longlands, Valsrivier, Sepane, Swartland, Bonheim, Sterkspruit, Mayo, Glenrosa, Dresden and Mispah (The Biodiversity Company 2024a).

Pre-mining vegetation types

The mine is situated within the grassland biome, which is known to experience summer rainfall and dry winters with frost and fire. These conditions are unfavourable for tree growth, hence the area was dominated by a single layer of grasses. On a fine scale, the mine area overlaps with the Soweto Highveld Grassland and Eastern Highveld Grassland vegetation types. The former was dominated almost entirely by *Themeda triandra* and accompanied by a variety of other grasses such as *Elionurus muticus*, *Eragrostis racemosa*, *Heteropogon contortus* and *Tristachya leucothrix.* The latter was dominated by the usual highveld grasses such as *Aristida*, *Digitaria*, *Eragrostis*, *Themeda*, *Tristachya* etc. (The Biodiversity Company 2024b).

Pre-mining land capability

Surrounding land uses included industrial complexes, power generation facilities, mining and agricultural activities. Pre-mining land capability classes are shown in Table 2.

Mine C

Study sites

Three differently aged, rehabilitated sites within mine C were selected. These were C (10), C (15) and C (30).

Topography and climate

The mine lies within the Transvaal Highveld Region with an elevation between 1 502 and 1 650 m a.s.l. The gently undulating topography is typical of the region. The northern areas drain towards the Spookspruit, while the southern areas drain towards the Boesmankranspruit, a tributary of the Olifants River. The mean annual temperature within the study area ranges from 12 °C to 20 °C, while mean annual precipitation ranges from 500 mm to 800 mm, most of which falls mainly during early to mid-summer months. Frost is experienced in winter (Jones and Wegener 2006).

Geology and soils

The mine falls within the Witbank Coalfield, which consists of sedimentary rocks of the coal-bearing Ecca Group of the Karoo Sequence. Five coal seams are contained in a 70 m average thick succession in the coalfield, consisting primarily of sandstone with subordinate siltstone and mudstone. The succession is the Vryheid Formation of the lower Ecca Group and followed the deposition of the Dwyka – the latter is of glacial origin and comprises mainly tillite. Underneath the Dwyka in the area is a volcanic pre-Karoo floor. This basement consists mainly of rhyolitic rocks of the Rooiberg Group, Pretoria (Jones and Wegener 2006).

Pre-mining vegetation types

The study area comprised largely grassland and moist grassland vegetation. In addition, cultivated areas (mainly maize or pasture) and alien invasive bush clumps with trees such as *Eucalyptus* species or *Acacia mearnsii* (black wattle) were observed. The grassland vegetation community was subdivided into three sub-communities based on past and current land uses, namely: disturbed grassland, grazed grassland and natural grassland. The dominant grasses within these sub-communities comprised *Eragrostis curvula*, *Hyparrhenia hirta*, *Cynodon dactylon*, *Boophane disticha*, *Eucomis autumnalis*, *Hypoxis hemerocallidea*, *Gladiolus crassifolius* and *Eulophia ovalis* subsp. *bainesii* (Strategic Environmental Focus 2012).

Pre-mining land capability and land use

The study area comprised cultivated lands, rehabilitated areas, alien invasive tree clumps (mainly *Eucalyptus* trees), grassland (disturbed and natural) and moist grasslands (wetlands), as well as pans and dams. Most of the grassland areas were grazed, historically cultivated or disturbed. Land uses comprised mainly cattle grazing, maize cultivation and coal mining (Strategic Environmental Focus 2012). According to Jones and Wegener (2006), the areas of the various land capability classes that existed before mining, and that were going to be disturbed, are presented in Table 3.

Table 3: Impact on land capability due to mining activities in mine C

Land capability class	North and south sections area (ha)	
	Pre-mining	Post-mining
Arable land	5 440	5 006
Grazing land	3 667	3 990
Wilderness	463	1 157
Wetland – pans and dams	1 560	977
Total	11 130	11 130

Source: Jones and Wegener (2006)

Field, laboratory and statistical procedures

Sampling dates

According to the Witbank (closer to mines A and C) and Leandra (closer to mine B) weather stations, the highest mean monthly temperature and rainfall in all three study sites are experienced and received between October and March (hot-wet season), as shown in Figure 2. On the other hand, the May–September period is characterised by the lowest temperature and rainfall (cold-dry season). Therefore, these are the periods during which great variations in veld productivity may be observed. For these reasons, veld condition assessment was carried out in March 2023, which was termed as Harvest A (HA). In the cold-dry season, plants normally dry up and lose their inflorescence, which complicates species identification. Thus, veld condition assessment was not undertaken in August 2023 (HB). To understand the extent of veld recovery after the cold-dry season, the assessment was carried out again in January 2024 (HC).

Table 4: Illustration of calculation of EI and %VCS

Grazing Status	Species count	%	Grazing value	Weights
Dec	28	46	10	459
Inc 1	0	0	7	0
Inc 2	30	49	4	197
Inc 3	0	0	1	0
Exotic	3	5	1	5
Total	61	100	EI	660.7
			%VCS	66.1

Source: Van Rooyen et al. (1996)

Species composition, ecological index (EI) and percentage veld condition score (%VCS)

Within each rehabilitated site, four transects, each measuring 100 m, were established. Along each transect, estimates of proportional species composition were made using the step-point method as described by Mentis (1981). This was followed by calculation of the EI and %VCS, as highlighted in (a) to (d) below and exemplified in Table 4.

a. The species that were recorded in the step-point survey were classified into their relevant ecological categories, namely decreasers (Dec), increasers 1 (Inc 1), increasers 2 (Inc 2), increasers 3 (Inc 3) and exotic.
b. The percentage composition of each of the ecological categories was then multiplied by the specific grazing value of each category.
c. The sum of these values represents an EI. This index has a maximum value of 1 000.
d. According to Van Rooyen et al. (1996), the EI values must be expressed as a percentage of a similar index of a reference point where the veld is in excellent condition (benchmark site). This is done to obtain a percentage veld condition score that is used in the determination of the grazing capacity of an area.

Basal cover

Basal cover was calculated as shown in Table 5.

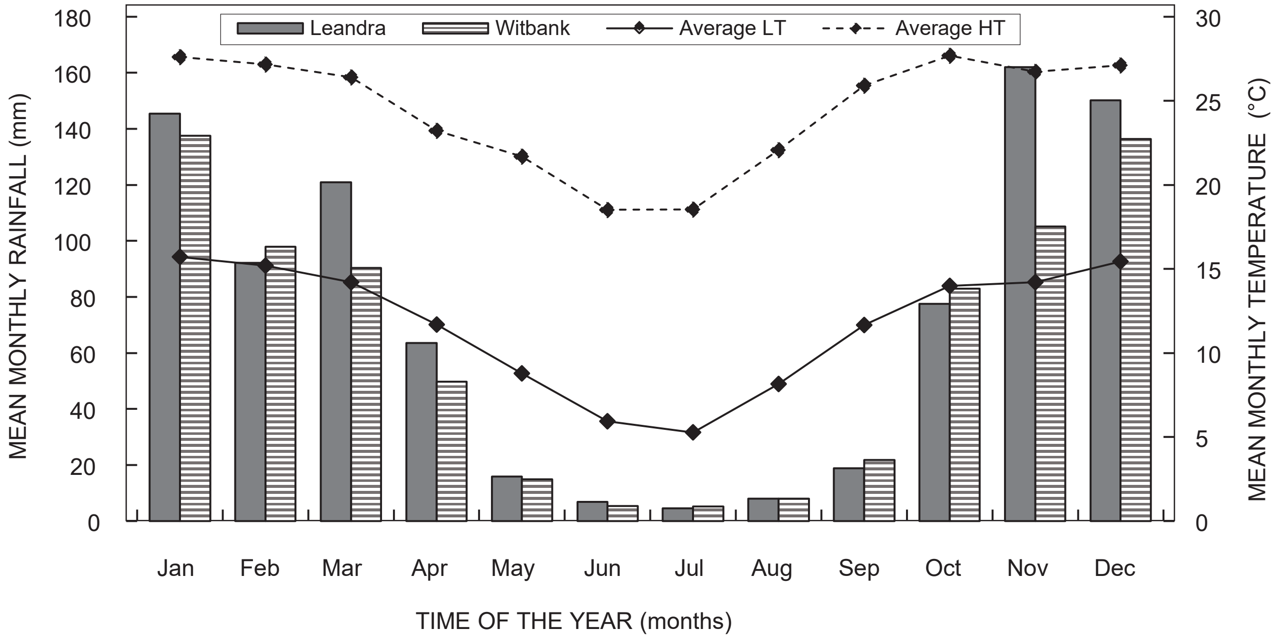

Figure 2: Mean monthly temperature (for all study sites) and rainfall (Witbank: for mines A and C; Leandra: for mine B) in Mpumalanga, South Africa. LT = low temperature; HT = high temperature

Table 5: Illustration of calculation of basal cover

Species	Total count	Total none strikes	Sum
Digitaria eriantha	18	5	23
Eragrostis curvula	12	18	30
Chloris gayana	3	2	5
Paspalum dilatatum	2	1	3
Total	35 (A)	26	61 (B)
Basal cover	A/B*100		57.4

Source: Van Rooyen et al. (1996)

Grazing capacity

Potential grazing capacity was calculated according to the equation given by Danckwerts (1989), as shown below:

$$GC = -0.03 + 0.00289(X1) + [(X2 - 419.7) \times 0.000633] \quad (1)$$

where: GC = grazing capacity in Large Stock Units (LSU) per hectare; X1 = percentage veld condition score; and X2 = mean annual rainfall in millimetres per year.

Estimation of biomass production

Estimation of biomass production was carried out in March 2023 (HA), August 2023 (HB) and January 2024 (HC). In August 2023, some sites, namely A (30), B (9) and C (15), had been affected by winter veld fires, and so there are no results for these sites because there was no biomass to collect.

Within each rehabilitated site, four transects, each measuring 100 m, were established. Within each transect, four plots each measuring 1 m × 1 m were established (i.e. there were 16 plots in each site). One biomass sample was collected from each plot, using a pair of shears (i.e. 16 biomass samples were collected from each site). Samples were stored in brown paper bags and, on the same date of sampling, the wet weight of all herbaceous matter was recorded using a mass balance. After drying at 55–60 °C for 48 hours, the dry weight was also recorded. Biomass production in tonnes dry matter per hectare was obtained by determining the difference between the wet and dry weights (Danckwerts and Trollope 1980).

Soil sampling and cover soil depth estimation

One soil sample was collected from the top 0–30 cm of each of the four plots in each transect. The four samples were homogenised together before chemical analyses (i.e. there were four homogenised soil samples per site). Besides the significance of the top 0–30 cm as the nutrient-rich zone, as highlighted in the Discussion section, plant establishment, survival and productivity also depend on deeper soils to enable optimum root development. Therefore, after soil collection, the auger was reinserted into the hole and driven further to estimate the depth of root penetrable soil. At the depth where the auger could no longer penetrate the soil, it was removed and the length of its sunken part was determined using a measuring tape attached to a wooden rod.

Chemical analyses

Chemical analyses were carried out at Intertek Testing Services; a private laboratory based in Pretoria, South Africa. In most methods, cations, boron, molybdenum, cobalt, silicon, etc. are tested separately. Further, each test has a separate cost. Therefore, in order to avoid exorbitant costs, the Mehlich III method was chosen because it is able to give results for a number of soil parameters in one test. This method was used to determine plant-available soil macronutrients (Na, K, Ca, Mg and S) and micronutrients (Fe, Mn, Cu, Zn, B, Mo, Al and Ni), as explained by Mehlich (1984). The *Manual of Soil Analysis Methods* of the Fertilizer Society of South Africa (1974) was used to determine P (Bray 2), cation exchange capacity

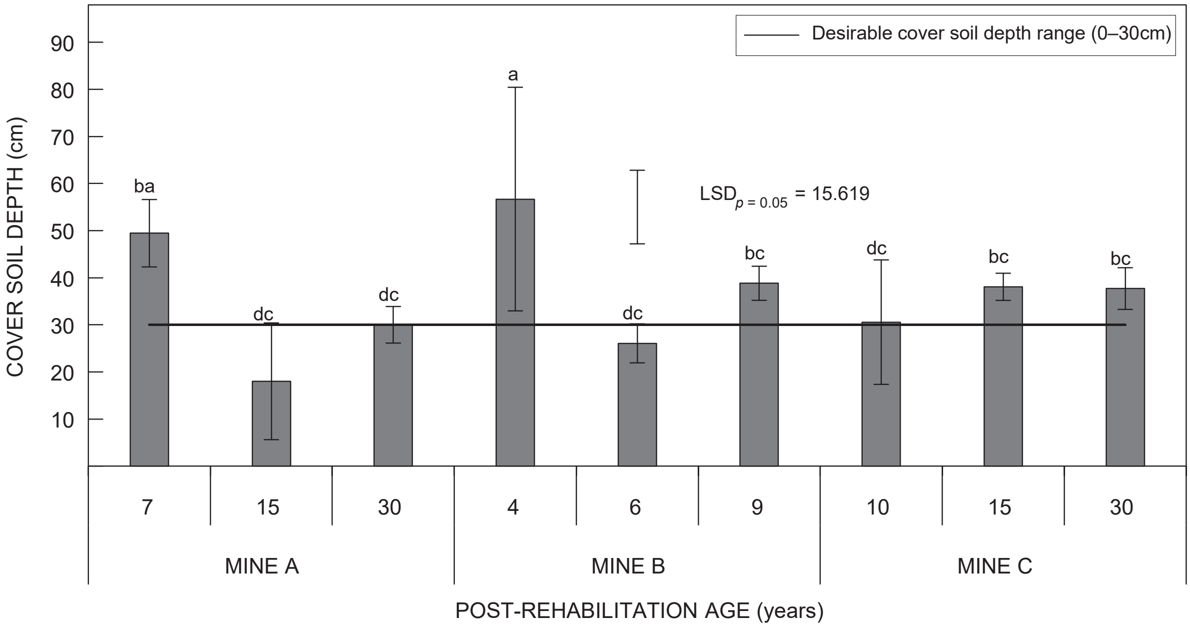

Figure 3: Mean cover soil depth of differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa. Means with the same letter are not significantly different ($p > 0.05$) from each other (*t*-tests; LSD). Error bars are standard deviations from means

CEC and pH (H_2O). The study focused on plant-available micronutrients for a number of reasons. Firstly, metals in soil exist in various geochemical forms, including plant-available (bioavailable) and total fractions (Speir et al. (2003). Total metal concentrations can neither be used to predict the transfer of toxic elements in the food chain (Dai et al. 2004), nor give accurate indication regarding risks related to metal contamination, including phytotoxicity and leaching risks (Barbafieri et al. 2013). On the other hand, plant availability refers to the quantity of a chemical that is available to living biota (Naidu et al. 2008a), which can be used as an indicator of potential risk that chemicals pose to the environment and human health (Naidu et al. 2008b). With regard to Na, K, P, Ca, Mg and S, these are amongst the nine macronutrients that are required by plants in large quantities (Brouder and Volonec 2020) for various functions in plants, as explained by Forth 1990; Wild 1995; Alloway 2013; Haygarth et al. 2013; White and Greenwood 2013.

Statistical analyses

Plant and soil data were subjected to analysis of variance (ANOVA) using the GLM (General Linear Models) Procedure of SAS software, version 9.4 (SAS Institute 2023). The Shapiro-Wilk test was performed on the standardised residuals to test for non-normality. As highlighted above under Field, laboratory and statistical procedures, there were 16 biomass samples and 16 soil samples from each site. Therefore, the Shapiro–Wilk test was chosen for this study because it is more appropriate for small sample sizes (< 50 samples), while Kolmogorov–Smirnov test is used for $n \geq 50$ (Shapiro and Wilk 1965). When there was significant deviation from normality and it was due to skewness, outliers were removed until the residuals had a normal or symmetric distribution (Glass et al. 1972). Means of significant effects were separated using Fisher's least significant difference (LSD) at the 5% level of significance. The Fisher's LSD was more appropriate because the purpose was to identify differences in means (Ott 1998). Pearson correlation coefficients were calculated on all measured parameters for the three individual mines, using XLSTAT (Addinsoft 2024).

The data were further subjected to principal component analysis (PCA) with correlation matrix to investigate the relationship between mines and age of the mines (factors) and a number of variables. The relationship between factors and variables was portrayed in a PCA biplot (where the first two principal components were plotted against each other). An Agglomerative Hierarchical Cluster analysis (AHC) with Ward's method was performed on the PCA factor scores to define groups within the factors. A linear discriminant analysis (LDA) was performed to determine whether mines and age of mines (groups) could be separated by the variables (in question). The discriminant analysis plot showed separation between the groups. These statistical analyses were implemented using XLSTAT (Addinsoft 2024).

Results

Soil physicochemical conditions

Soil depth

With the exception of A (15) and B (6), cover soil depth in all other sites was > 30 cm. In mines A and B, soil depth was significantly higher ($p < 0.05$) in the youngest sites than in the oldest ones. In mine C, soil depth was higher in the two oldest sites (Figure 3).

Acidity

With the exception of C (15), pH was ≥ 5.1 in all sites. Generally, there was an increase in pH with each increase in rehabilitation age in mine A, with significant differences ($p < 0.05$) between A (7, 15) and A (30). In mine B, the lowest pH was observed in the oldest site. In mine C, the highest pH was found in C (30) (Table 6).

Macronutrients

In all mines, P concentrations were higher in the oldest sites compared to the youngest ones, with significant differences ($p < 0.05$) between A (7) and A (30). Generally, the highest levels of P concentrations were observed in mine A, followed by mine C. Despite having the lowest concentrations of P, a clear trend was observed within mine B. Each increase in site age resulted in an increase in P (Table 6).

Notably, the levels of Na, K, Ca and Mg were significantly higher ($p < 0.05$) in mine B than in mines A and C. Within mine A, each increase in site age resulted in an increase in K, Ca and Mg levels, with significant differences ($p < 0.05$) between A (7) and A (15, 30); A (7), A (15) and A (30); A (7, 15) and A (30), respectively. Although there were variations in the levels of P (3–3.8 mg kg^{-1}), Na (23.7–26.8 mg kg^{-1}) and K (190.5–212.5 mg kg^{-1}) in mine B, there were no statistical differences ($p > 0.05$) between the sites. In mine C, the levels of Na, K, Ca, Mg and S were higher in the youngest than in the oldest site. A similar trend was observed in the levels of P and Na in mine C. The levels of S did not show any perceptible trend in mines A and B; however, there were significantly ($p < 0.05$) higher levels in the oldest sites than in the youngest ones. Within mine C, each increase in site age corresponded with a decrease in S levels from about 55 to 32 mg kg^{-1} (Table 6).

CEC

CEC was significantly higher ($p < 0.05$) in mine B (7.3–7.9 meq/100 g) than in mines A (1.5–6.5 meq/100 g) and C (1.3–2.5 meq/100 g). Within mine A, each increase in site age corresponded with a significant increase ($p < 0.05$) in CEC. In mines B and C, the levels of CEC did not follow any particular trend. Further, there were no statistical differences between the oldest and the youngest sites. Notably, CEC was < 10 meq 100g^{-1} in all sites (Table 6).

Micronutrients

Within mine A, each increase in site age corresponded with significant increase ($p<0.05$) in the levels of Mn, Cu and Ni. For Cu, this trend was observed in mines B and C, with significant differences between the youngest and the oldest sites. Notably, B, Mo and Ni did not exceed 1.5 mg kg^{-1} in all sites. Apart from Cu, there were generally no perceptible trends in the levels of micronutrients in mines B and C, however, Fe, Zn, Al, and Ni values were higher in the oldest site than in the youngest site in mine C. The same trend was observed in the values of Mn, Zn, B and Al in mine C (Table 7).

PCA

According to the results of the PCA, which was performed on the complete data set obtained from the soil analysis, there

Table 6: Acidity (pH) and macronutrient characterisation (mean ± SD) of soils from the differently aged, rehabilitated coal mined sites in Mpumalanga, South Africa

Mine	Site age (years)	pH	P (Bray)	Na	K	Ca	Mg	S	CEC
		(H$_2$0)			(P – S: mg kg^{-1})				(meq/100 g)
A	7	5.1 ± 0.1dc	7.6 ± 1.7d	18.0 ± 0.8d	70.0 ± 18.2de	159.5 ± 24.8e	45.8 ± 12.1e	44.0 ± 11.1cbd	1.5 ± 0.3de
	15	5.2 ± 0.1c	55.0 ± 8.5a	18.3 ± 1.2dc	94.3 ± 7.5dc	329.7 ± 9c	72.3 ± 6.4ed	29.9 ± 3.4fe	2.6 ± 0.1c
	30	5.7 ± 0.5b	39.0 ± 4.7b	22.0 ± 4.3bc	102.5 ± 6.9c	762.33 ± 191.4b	228.5 ± 17.7c	102.7 ± 15.5a	6.5 ± 1.6b
B	4	6.2 ± 0.3a	3.0 ± 0.8d	24.5 ± 3.7ba	198.0 ± 9.2a	820.0 ± 100.7b	308.8 ± 34.1b	25.7 ± 7.3f	7.3 ± 0.7ba
	6	6.4 ± 0.2a	3.5 ± 1.3d	23.7 ± 3.8ba	212.5 ± 11.6a	964.8 ± 59.4a	296.3 ± 14.9b	20.9 ± 2.7f	7.9 ± 0.2a
	9	5.8 ± 0.2b	3.8 ± 0.5d	26.8 ± 2.6a	190.5 ± 24.9a	801.3 ± 147.7b	363.7 ± 37.6a	46.2 ± 11.5cb	7.4 ± 1.2ba
C	10	5.1 ± 0.2c	19.8 ± 10.3c	17.3 ± 0.5d	160.8 ± 28.3b	241.5 ± 49.5dc	98.5 ± 22.4d	54.7 ± 4.6b	2.5 ± 0.4dc
	15	4.8 ± 0.1d	26.8 ± 9.9c	17.5 ± 1.3d	55.0 ± 15.2e	133.0 ± 55.4e	45.0 ± 18.5e	39.7 ± 11ced	1.3 ± 0.5e
	30	5.2 ± 0.2c	25.3 ± 4c	16.5 ± 0.6d	87.3 ± 21dc	214.8 ± 85de	59.8 ± 23.3e	31.5 ± 5.5fed	1.9 ± 0.7dce

Means with the same letter in the same column are not significantly different ($p > 0.05$) from each other (*t*-tests)
LSDs: pH = 0.36 P (bray) = 8.76 Na = 3.79 K = 26.25 Ca = 141.7 Mg = 36.34 S = 13.29 CEC = 1.13

Table 7: Micronutrient characterisation (mean ± SD) of soils from the differently aged, rehabilitated coal mined sites in Mpumalanga, South Africa

Mine	Site age (years)	Fe	Mn	Cu	Zn	B	Mo	Al	Ni
					(Fe – Ni: mg kg^{-1})				
A	7	47.6 ± 10cd	11.9 ± 2.2f	1.3 ± 0.1f	2.4 ± 0.5c	0.5 ± 0.1bdc	1.1 ± 0.2a	508.9 ± 56.7bc	0.3 ± 0.0e
	15	117.5 ± 6.4a	21.0 ± 2.6e	1.9 ± 0.2cd	7.9 ± 1.8a	0.5 ± 0.0bac	0.8 ± 0.1bc	617.5 ± 54.9ba	0.8 ± 0.2cb
	30	77.0 ± 16.3b	45.8 ± 4.7ba	2.8 ± 0.5a	6.1 ± 1.3b	0.5 ± 0.0bdac	0.9 ± 0.2ba	416.3 ± 116.1c	1.5 ± 0.2a
B	4	46.1 ± 10.6cd	35.9 ± 0.5c	1.8 ± 0.4cde	2.2 ± 0.6c	0.4 ± 0.1dc	0.8 ± 0.2bc	518.3 ± 147.4bc	0.8 ± 0.1c
	6	49.9 ± 5.9cd	48.3 ± 3.7a	2.2 ± 0.2cb	2.1 ± 0.2c	0.5 ± 0.1a	0.9 ± 0.1bac	544.2 ± 34.6ba	1.0 ± 0.0b
	9	45.0 ± 8d	41.4 ± 5.8b	2.4 ± 0.1b	2.4 ± 0.2c	0.5 ± 0.0ba	0.8 ± 0.3bc	610.5 ± 24.8ba	0.8 ± 0.0c
C	10	66.5 ± 13.6cb	28.0 ± 4.3d	1.5 ± 0.1fe	5.2 ± 1.7b	0.4 ± 0.0d	0.7 ± 0.2bc	596.0 ± 49.5ba	0.5 ± 0.0ed
	15	109.9 ± 26.5a	9.8 ± 1.6f	1.6 ± 0.1fde	3.5 ± 0.8c	0.5 ± 0.0bdc	0.8 ± 0.2bac	576.1 ± 36.8ba	0.4 ± 0.1ed
	30	98.9 ± 14.8a	12.2 ± 3.5f	1.7 ± 0.0de	6.2 ± 1.6b	0.4 ± 0.0dc	0.7 ± 0.2c	640.0 ± 46.9a	0.6 ± 0.1d

Means with the same letter in the same column are not significantly different ($p > 0.05$) from each other (*t*-tests)
LSDs: Fe = 20.82 Mn = 5.45 Cu = 0.33 Zn = 1.64 B = 0.08 Mo = 0.25 Al = 110.45 Ni = 0.17

was correlation between the different soil attributes. The first principal component (F1) accounted for 48.39% of the total variation in the data. The second principal component (F2) accounted for a further 17.53% of the total variation. Figure 4, which is a two-dimensional representation of all the soil physiochemical data, accounted for 65.91% of the total variation in the data. Many of the macronutrients (Na, Mg, K, Ca), pH, CEC and Mn were positively correlated with the differently aged, rehabilitated sites of mine B. On the other hand, the micronutrients Ni and Cu were positively correlated with A (30), and Fe and N with A (15).

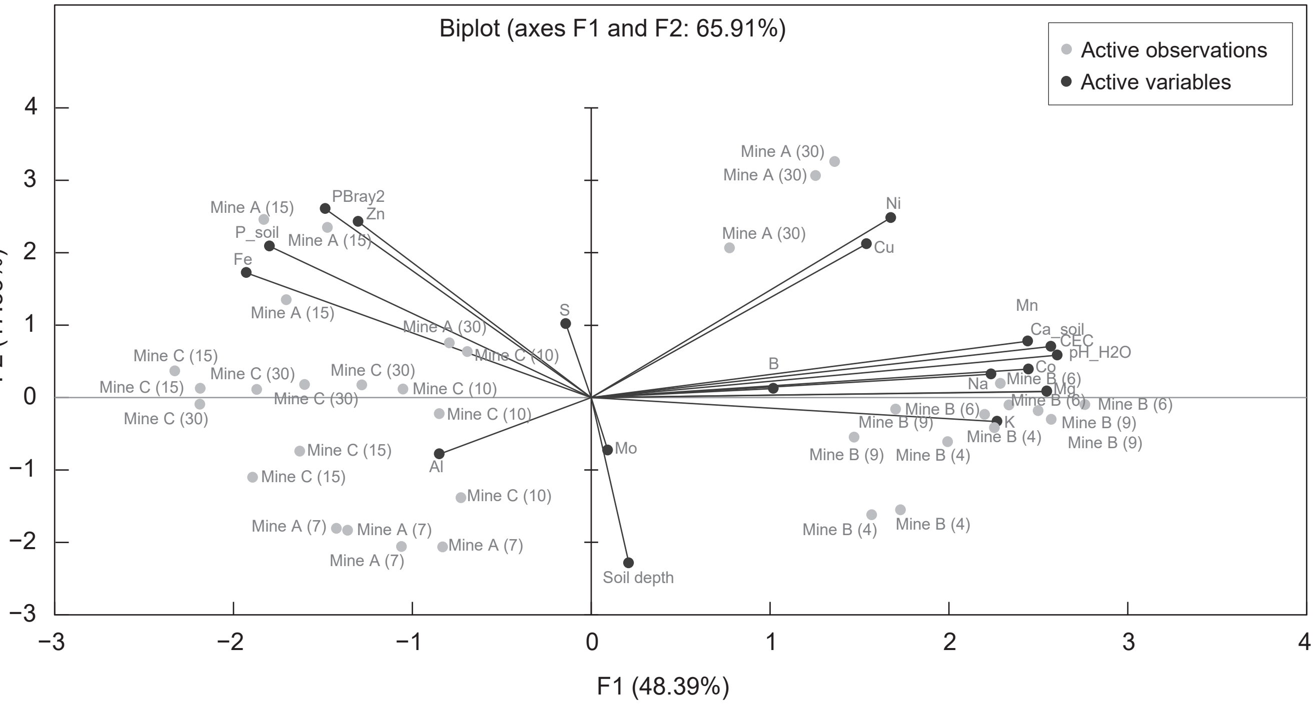

Figure 4: Principal component analysis biplot of soil parameters in differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa

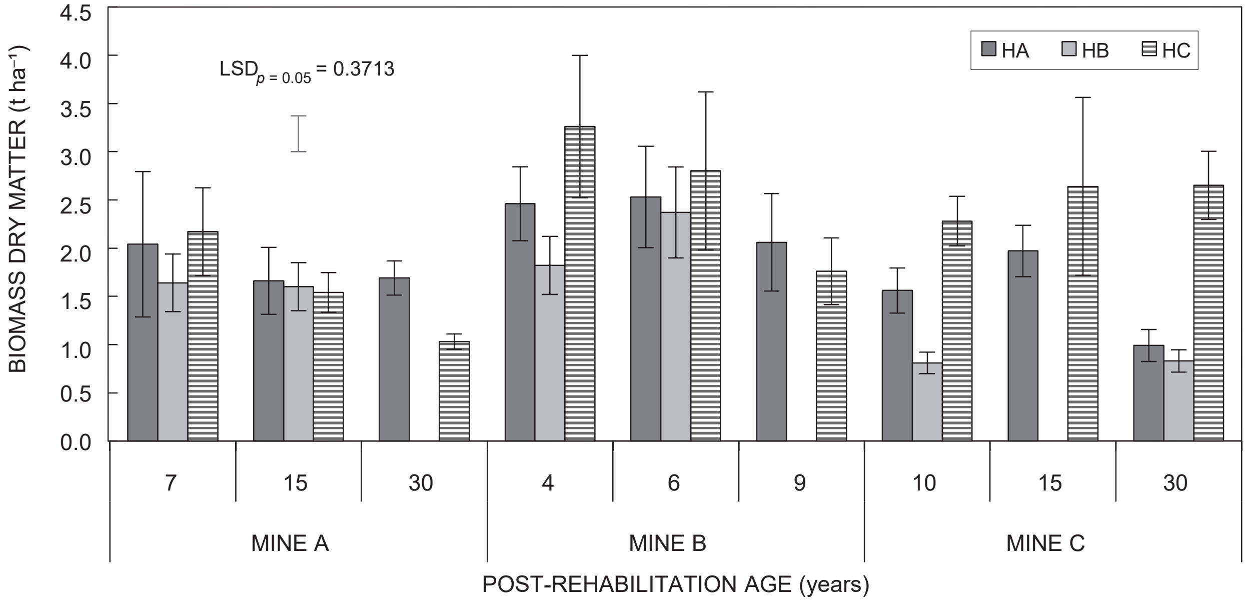

Figure 5: Mean biomass production in pastures established in differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa. Error bars are standard deviations from means.

Table 8: Plant species identified in the differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa

Species	Ecological status					Grazing value		
	Dec	Inc 1	Inc 2	Inc 3	Exo	High	Aver.	Low
Digitaria eriantha	✓					✓		
Eragrostis curvula			✓			✓		
Eragrostis rigidor			✓				✓	
Sporobolus africanus				✓				✓
Eragrostis chloromelas			✓				✓	
Cynodon dactylon			✓			✓		
Heteropogon contortus			✓				✓	
Eragrostis gummiflua			✓					✓
Pognarthria squarrosa			✓					✓
Chloris gayana	✓					✓		
Pennisetum clandestinum					✓	✓		
Melinis repens	✓							✓
Paspalum notatum					✓		✓	
Aristida congesta subsp. Congesta			✓					✓
Cymbopogon plurinodis – Inc 3				✓				✓
Paspalum dilatatum					✓	✓		
Imperata cylindrica		✓						✓

Dec = decreaser Inc = increaser Exo = exotic Aver. = average

Table 9: Characterisation of sown (in plain text) and naturally recruited (in **bold** text) plant species observed within differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa

	Mine A
Sown species	Species identified during the survey
Eragrostis teff	*Chloris gayana*
Chloris gayana	*Digitaria eriantha*
Digitaria eriantha	*Cynodon dactylon*
Cynodon dactylon	***Eragrostis curvula***
	Eragrostis rigidor
	Eragrostis chloromelas
	Heteropogon contortus
	Eragrostis gummiflua
	Pognarthria squarrosa
	Pennisetum clandestinum
	Melinis repens
	Paspalum notatum
	Aristida congesta subsp. ***congesta***
	Mine B
Sown species	Species identified during the survey
Chloris gayana	*Chloris gayana*
Digitaria eriantha	*Digitaria eriantha*
Eragrostis curvula	*Eragrostis curvula*
Eragrostis teff	***Pennisetum clandestinum***
Cenchrus cilliaris	***Cymbopogon plurinodis – Inc3***
Antepora pubescens	***Paspalum dilatatum***
	Mine C
Sown species	Species identified during the survey
Eragrostis teff	*Digitaria eriantha*
Digitaria eriantha	*Eragrostis curvula*
Panicum maximum	*Chloris gayana*
Medicago sativa	***Eragrostis chloromelas***
Avena sativa L.	***Pennisetum clandestinum***
Eragrostis curvula	***Paspalum dilatatum***
Chloris gayana	

Note: All species were identified through the herbaceous survey step-point method. However, additional information on sown species was obtained through pers. comm., M. Platt, 22 August 2024; M. van Wyk, 19 August 2024; P. Lukhombo, 30 August 2024

Veld conditions

Biomass production

Biomass production at HA was higher in the youngest sites than in the oldest ones; however, these differences were insignificant ($p > 0.05$). At HC, there was a decrease in biomass production with each increase in site age in mines A and B. On the other hand, each increase in site age in mine C seemed to correspond with an increase in biomass production. Across all sites, the highest biomass production at HA and HC was found in B (6) and B (4), respectively. With the exception A (15), the general trend of biomass production was HC > HA > HB within all sites that were not affected by winter veld fire (Figure 5).

Plant species

A total of 17 species were recorded in all study sites (Table 8). These consisted of the original species mix sown during rehabilitation as well as those that were spontaneously recruited into the rehabilitated sites (Table 9).

Ecological status abundance

There was a significant decrease ($p < 0.05$) in the abundance of increaser 2 species with each increase in rehabilitation age in mine A (HA). A similar trend (although not always significant) was observed at (HC) and in increaser 3 species at HA. As for decreaser species, there were no clear trends. However, they were the most abundant in most sites, namely; A (15), B (4), B (6), B (9), C (10), C (30) (at HA) and C (15) (at HC) (Table 10). At both harvests, there was a significant increase in the abundance of exotic species with each increase in site age within mine A. Although this trend was not maintained in mines B and C, there were significantly more exotic species in the oldest sites than in the youngest ones.

Basal cover (BC)

BC was generally higher in the oldest sites than in the youngest ones. Within all sites, BC was significantly higher

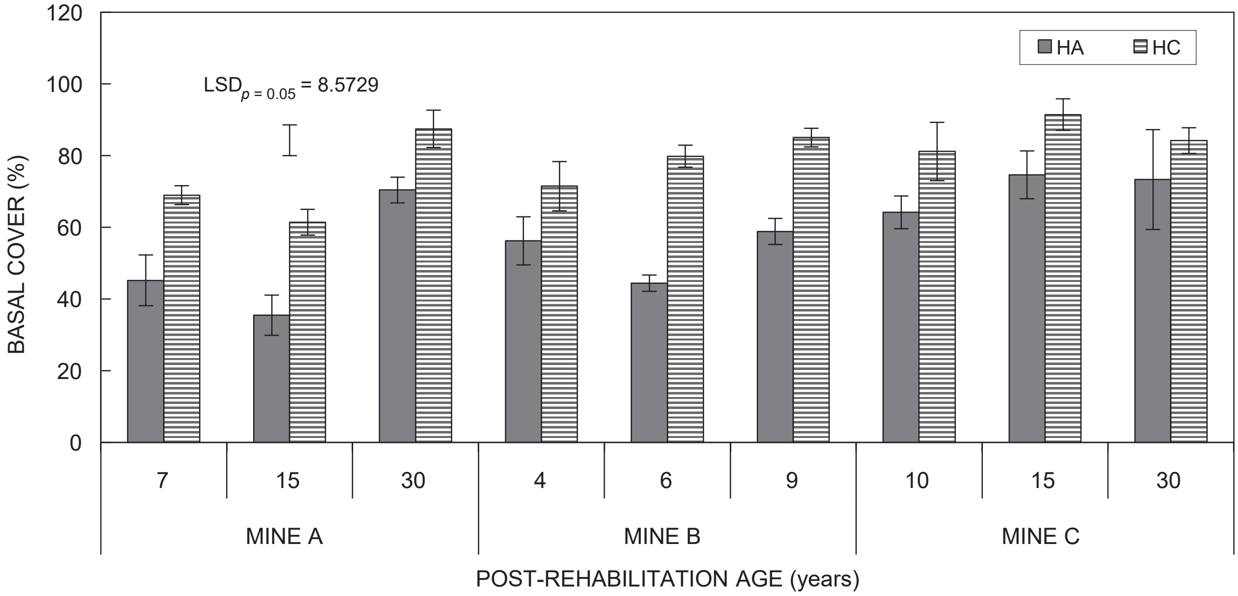

Figure 6: Basal cover of pastures established in differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa. Error bars are standard deviations from means

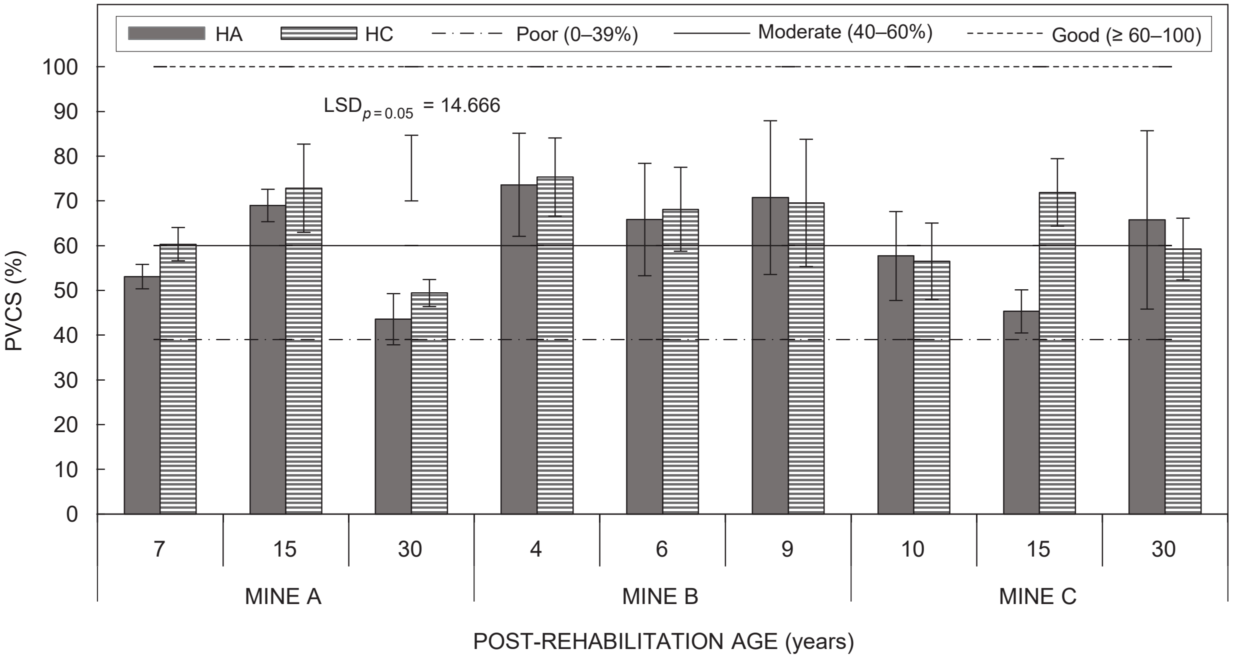

Figure 7: Percentage veld condition scores (PVCSs) of pastures established in differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa. Error bars are standard deviations from means

($p < 0.05$) at HC than at HA. Notably, BC in eight of the nine study sites was > 30% at both harvests (Figure 6).

Percentage veld condition scores (and grazing capacity

Percentage veld condition scores (PVCSs) did not follow any noticeable trend; however, they were > 40% in all sites; the highest (66–75%) being in mine B. Within sites, PVCSs in A (7), A (15), A (30), B (4), B (6) and C (15) were slightly higher at HC than at HA; however, these differences were insignificant ($p > 0.05$) (Figure 7). Within the same sites highlighted above, grazing capacity values were slightly higher at HA than at HC; however, these differences were generally insignificant. Noticeably, grazing capacity values for all harvests in mines A and C were slightly higher (2.8–3.6 and 2.8–3.5 ha LSU^{-1}, respectively) than in mine B (2.7 – 3 ha LSU^{-1}) (Figure 8).

Table 10: Ecological status of different grass species within the differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa

Mine	Site age (years)	Dec HA (%)	Dec HC (%)	Inc 2 HA (%)	Inc 2 HC (%)	Inc 3 HA (%)	Inc 3 HC (%)	Exo HA (%)	Exo HC (%)
A	7	22.5 ± 5.1gf	34.1 ± 6.2edcf	73.0 ± 5.5ba	65.0 ± 6.3bc	2.5 ± 1.0de	0.8 ± 1.0e	0.0 ± 0.0d	0.0 ± 0.0d
	15	51.3 ± 6.4ebdac	58.7 ± 16.0ba	42.7 ± 7.6de	32.0 ± 15.0def	2.3 ± 1.2de	3.3 ± 2.9dce	4.0 ± 1.0dc	5.7 ± 3.5dc
	30	30.0 ± 6.1egf	33.5 ± 5.4edf	21.8 ± 2.6f	31.3 ± 7.1def	0.0 ± 0.0e	0.0 ± 0.0e	48.5 ± 7.0a	35.3 ± 2.9b
B	4	60.0 ± 17.8a	61.0 ± 14.9a	32.5 ± 18.0def	25.0 ± 10.1ef	7.8 ± 9.6dc	9.0 ± 4.4c	0.0 ± 0.0d	0.0 ± 0.0d
	6	46.8 ± 17.0ebdac	52.1 ± 12.7bdac	46.0 ± 11.6dc	36.8 ± 8.1def	0.0 ± 0.0e	0.0 ± 0.0e	7.3 ± 9.4dc	10.8 ± 7.0c
	9	53.8 ± 27.9bdac	51.3 ± 22.8ebdac	41.5 ± 26.0de	45.0 ± 20.7d	0.0 ± 0.0e	0.0 ± 0.0e	5.0 ± 1.6dc	3.8 ± 2.1dc
C	10	43.8 ± 13.8ebdacf	37.5 ± 14.4ebdcf	28.0 ± 13.6def	42.3 ± 19.6de	28.3 ± 10.6a	20.0 ± 10.2b	0.0 ± 0.0d	0.0 ± 0.0d
	15	8.8 ± 7.9g	55.3 ± 10.5bac	91.3 ± 7.9a	40.0 ± 7.4def	0.0 ± 0.0e	0.0 ± 0.0e	0.0 ± 0.0d	4.8 ± 5.6dc
	30	48.5 ± 24.6ebdac	32.7 ± 10.0edf	40.3 ± 14.8def	65.8 ± 7.4b	0.0 ± 0.0e	0.0 ± 0.0e	11.3 ± 19.9c	1.5 ± 3.0d

Means with the same letter in the same column are not significantly different ($p > 0.05$) from each other (*t*-tests)
LSDs: Dec = 21.64 Inc 2 = 19.04 Inc 3 = 6.36 Exo = 8.80

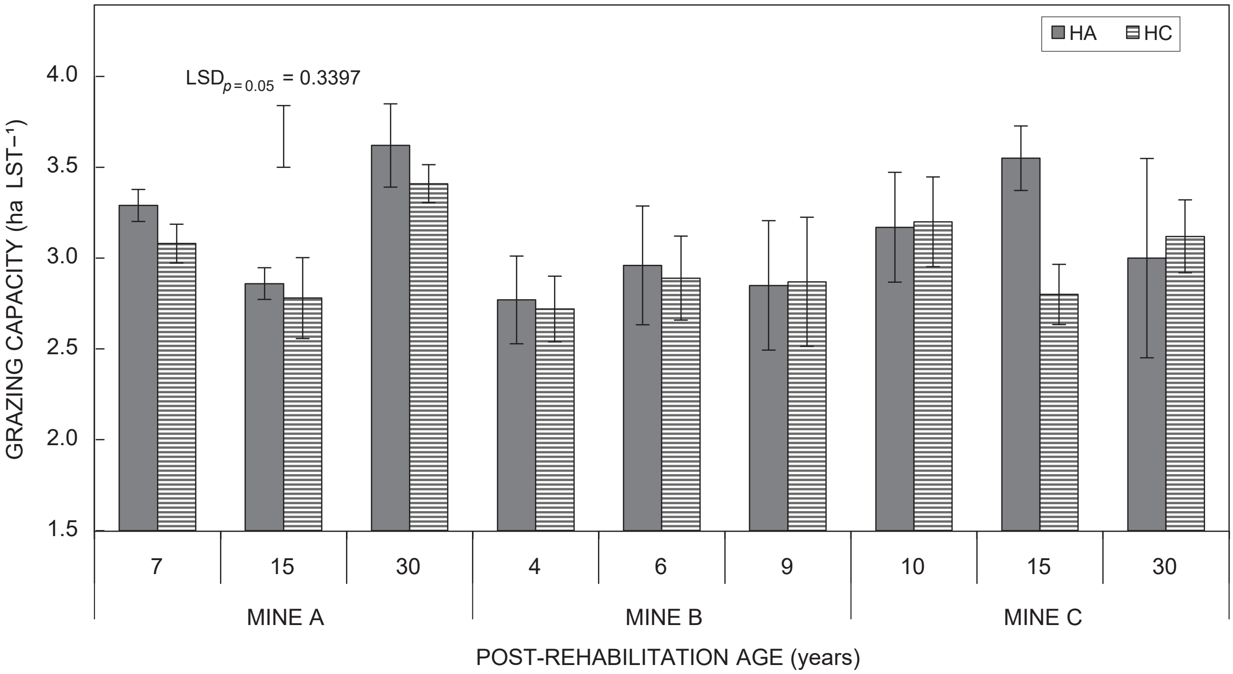

Figure 8: Grazing capacity of pastures established in differently aged, rehabilitated surface coal mined sites in Mpumalanga, South Africa. Error bars are standard deviations from means

Discussion of results

Soil depths

Generally observed soil depths of $>$ 30 cm in seven of the nine study sites were considered satisfactory because this is the depth that is associated with the abundance of organic matter (Hillel 2008) and nutrients (Forth 1990). The greatest density and diversity of microorganisms are also concentrated in the top 15–25 cm of soil, because this is the zone where there are plentiful C substrates (White 2006). Therefore, the soil depths observed in this study were deemed satisfactory for essential interactions between soil conditions that influence plant growth.

Soil physicochemical conditions

According to the description of pH levels by Dickinson (2002) and Jones (2012), A (7), A (15) and all sites in mine C (i.e. five of the nine study sites) were thought to be strongly acidic (pH 4.5–5.5); an acidity level associated with high mobility and availability of potentially toxic elements. This is a concern because when soils become acidic, their capacity to adsorb cations is reduced so that nutrient cations (especially Ca^{2+} and Mg^{2+}) pass into solution and are leached in drainage water. As the pH decreases further, the concentrations of aluminium ions ($Al(OH)^{2+}$, $AlOH^{2+}$ and Al^{3+}) begin to increase in soil solution and become dominant in that order, and they displace other cations from exchange sites (Forsberg and Ledin 2006; Carvalho et al. 2013).

On the other hand, pH in mine B was deemed suitable for a number of reasons. Firstly, the range was 5.8–6.4, which according to Dickinson (2002) and Jones (2012), is slightly acidic and linked with high mobility and availability of NO_3, PO_4, K, Mg, S, B and Cu. Secondly, 5.8–6.4 was thought suitable because it was well within the 5.5–7.0 range, which is the accepted pH range for fertile soils (Wild 1995; Schoeman 2001). Further, the recommended pH for most forage grasses and grass-legume mixtures is 5.5–6.5 and 6.0–7.0, respectively (Barker and Culman 2020).

A possible explanation for the generally acidic soils in the study sites was thought to be S. Considering average, minimum and maximum concentrations of nutrients in soil by Barker and Collins (2018), S levels observed in this study were much higher than plant requirements. When S levels rise, there is a tendency for soil to become more acidic (Bunton et al. 2020). One probable cause for the generally higher S levels was thought to be coal-burning practices. The Mpumalanga province is home to a cluster of 12 coal-fired power plants with a total capacity of over 32 gigawatts, owned and operated by the Electricity Supply Commission (ESKOM) (Alfreds 2018). Coal burning is one of the key causes of soil acidification, the chemistry of which is explained by Miller and Spoolman (2021).

In A (15) and A (30), and all sites within mine C, the observed P levels were considered adequate for several reasons. One study in South Africa, which evaluated P levels in rehabilitated coal mines in Mpumalanga, found P levels of 15–60, 25–60 and 5–45 mg kg^{-1} in three mines. For the first two mines, P levels were considered adequate (Schoeman 2001). In mine B, P levels increased with each increase in site age. These observations were similar to earlier findings by Boerner et al. (1998) and Adeli et al. (2013). The lowest levels of P concentrations were also observed in mine B. This was attributed to higher biomass growth that was found in mine B (see discussion under Biomass production), because P is one of the macronutrients required by plants in larger amounts, and so a larger proportion might have been absorbed by plants. Also, in A (7) and all sites in mine B, P concentrations were < 10 mg kg^{-1}; the threshold below which P is considered deficient for plants (Barker and Collins 2018).

K concentrations in mine A behaved similarly to P in mine B. Generally, these results were favourable because, in earlier studies, K values above 75 mg kg^{-1} in soils of rehabilitated coal mines in South Africa were considered adequate (Schoeman 2001). Further, levels of K in A (7), A (15), A (30), C (15) and C (30) were well above 50 mg kg^{-1}; the threshold below which K may be considered deficient (Barker and Collins 2018). With the exception of A (7) and C (15), Ca levels in all sites were > 200 mg kg^{-1}; the level below which Ca is considered inadequate for plants (Schoeman 2001; Barker and Collins 2018). Also, with the exception of A (7), C (15) and C (30), Mg concentrations in the rest of the sites were > 65 mg kg^{-1}, which according to Schoeman (2001) is considered adequate.

The observed low levels of CEC across all study sites were a cause for concern. According to Jones (2012), CEC < 10 meq/100 g is associated with a range of negative conditions including high sand content, low organic matter content, low capacity to hold plant nutrient elements, and loss by leaching from the soil profile. A possible explanation for the suboptimal levels of CEC was thought to be the generally acidic soils as explained earlier. According to Forth (1990), CEC is positively correlated with pH.

The low levels of micronutrients observed in this study were not a surprise because it is a well-researched fact that mine soils are deficient in soil nutrients, due to a host of conditions such as lack of organic matter, low pH, low CEC, etc. Although they were generally low, the values of Mn, Zn and B values remained higher than 10 mg kg^{-1}, 1 mg kg^{-1} and 0.1 mg kg^{-1}, respectively. These are the thresholds below which these micronutrients are considered deficient in soil (Barker and Collins 2018). Further, the levels of Cu, Zn and Ni were much lower than levels of concern, which are > 40 mg kg^{-1} Cu, > 400 mg kg^{-1} Zn and > 50 mg kg^{-1} Ni (Evanylo et al. 2005). These results were positive because, although they are essential for plant growth, micronutrients are required in lower amounts (Lopez-Arredondo et al. 2017; Brouder and Volonec 2020). Otherwise, if they are available in high levels, micronutrients can damage cell membranes, alter enzyme specificity, disrupt cellular functions and damage the structure of DNA in plants (Mohammed et al. 2011).

The high levels of Al observed in this study were linked to pH. As can be seen in Table 6, pH did not exceed 6.4 in all sites. Below pH 6.5, acidity is associated with increasing Fe and Al in soil solution. In terms of potential impacts, Al is associated with restricted root growth (Forth 1990).

A number of parameters (pH, Na, Mg, Ca, K, Mn and CEC) were highly loaded in mine B (6). This was attributed to pH, which was higher in B (6) than in all other sites. In mines A and C, pH was generally strongly acidic (low), but slightly acidic (high) in mine B. The positive influence of a higher pH in retaining macronutrients has already been highlighted above.

Biomass production

In all mines, biomass production was higher in the youngest sites, at HA. A similar trend was observed at HC in mines A and B. This was attributed to the initial application of fertilisers during rehabilitation, in line with current guidelines for the rehabilitation of surface coal mines in South Africa (Coaltech et al. 2019).

In the older sites, there was generally a decline in productivity. There were a number of possible explanations for this observation. Firstly, there is often a lack of ongoing efforts by mining companies to maintain optimum nutrient levels in rehabilitated mines. Secondly, stockpiled soil is normally applied as cover soil during rehabilitation. However, stockpiling is associated with a number of physicochemical problems in soil, including the reduction of pH (Gupta et al. 2019), soil organic carbon, nitrogen, below-ground biodiversity and abundance, soil water-holding capacity (Ezeokoli et al. 2019), seed viability (Dhar et al. 2019), nutrient cycling (Mackenzie and Naeth 2019; Fadaei et al. 2021), etc. Therefore, stockpiled soil may be sterile by the time rehabilitation efforts commence (Ghose and Kundu 2004). Based on the above, synthetic fertilisers have a limited duration of effectiveness and are incapable of adequately addressing depleted nutrients, which arise during stockpiling (Roberts et al. 2015). Secondly, the decline in productivity of the older sites was thought to be caused by hardsetting of soils. Hardsetting is a phenomenon that occurs in previously loosened soils (Osman 2014; Wang et al. 2017) of low organic matter (Greene et al. 2002; Canatoy and Daquiado 2021) whereby soils set to a hard, structureless mass during drying and collapse/slump when wetted (Mullins et al. 1990; Materechera 2009). This results to poor plant productivity as explained by Hillel (2008) and Canatoy and Daquiado (2021).

Across all mines, the highest levels of biomass production were observed in B (4) and B (6). In addition to the initial once-off application of fertilisers, cover soil depth, levels of acidity and mean monthly rainfall may have been some of the contributing factors. While the rehabilitation guidelines recommend a soil thickness of ≥ 0.25 m (25 cm) for Land Capability Class III (grazing) (Coaltech et al. 2019), the standard amount of cover soil depth that was applied in mine B is 0.8 m (80 cm) (Pers. Comm, M. van Wyk, 13 April 2023). This, therefore, could have provided plants with deeper soils for root development. Further, soils in mine B were in the medium acidity range (pH 5.6–6.0), which is associated with higher mobility and availability of most macronutrients (Dickinson 2002; Jones 2012). Additionally, according to Figure 2, mean monthly rainfall received in areas around mine B is higher during most of the hot-wet period, than in mines A and C. Decades of research have demonstrated a strong relationship between soil water availability and forage yield response, as described by Allen and McAdam (2020) and Volonec and Nelson (2020).

Generally, the biomass production trend in all mines was HC > HA > HB. Production was the lowest at HB because biomass collection at this time coincided with the cold-dry season, which is characterised by the lowest mean monthly temperature and rainfall (< 10–22 °C and < 10 mm per month, respectively). Rainfall is one of the single most limiting environmental factors influencing plant production and survival (Snyman 2005; 2006). Plants growing in a soil environment with reduced water availability have lower N uptake and decreased activity of N assimilation (Nguyen et al. 2017). Also, lower temperatures in winter are associated with inhibited nutrient and water transport, ion leakage, rapture of cell wall and cell membrane, dehydration of cells, damage to endoplasmic reticulum, unprovoked water movement (Khalil et al. 2018), etc. The higher biomass production at HC was ascribed to optimum temperature and rainfall, which may have led to increased green herbage (Mwangi et al. 2021; Lin et al. 2020).

Plant species and ecological status abundance

In addition to sown species, a number of naturally recruited species were identified in the study sites. This was viewed positively because spontaneous species perform better than introduced plants in terms of survival, growth and reproduction (Ha et al. 2019). They have better mechanisms to deal with harsh environments such as salinity, water stress (Al-Thani and Yasseen 2020), drought, low soil fertility and poor soil structure (Guterres et al. 2019). In the majority of sites, decreaser species were the most abundant. This was an important outcome because most surface coal mining companies in the Mpumalanga province aim to re-establish grazing land capability potential for the end land use option, instead of the original arable land capability (Mushia et al. 2016), since costs for other end land uses are much higher than for permanent pasture establishment (Weyer et al. 2017). The abundance of decreaser species is indicative of good veld condition (Du Plessis et al. 1998; Ngwenya 2012) and high forage production potential (Trollope et al. 1989). Further, they are the most palatable and the first to be selected by grazers (Abule et al. 2007).

Between the three mines, values for ecological status abundance were higher in mine B (47–60%) than in mines A (23–51%) and C (9–49%). As highlighted in the Biomass production section, soils in mine B were in the medium acidity range (pH 5.6–6.0), which is associated with higher mobility and availability of most macronutrients (Dickinson 2002; Jones 2012). Further, deeper soils, as also already highlighted, could have positively influenced species abundance in mine B than in other mines.

BC

The levels of BC observed in this study were about 36–75% in HA and 61–91% in HC. These results were considered satisfactory because an acceptable BC percentage in South Africa used a measure of grassland in good condition is 30–40% (Truter 2007) and 15% for the Mpumalanga Coalfields (Coaltech et al. 2019).

In all sites, BC was higher in the oldest than in the youngest sites at both harvests. This was thought to be a result of leaf litter accumulation and decomposition over the years. This leads to gradual incorporation of nutrients and organic materials into the soil, reactivating the nutrient cycle, the growth of vegetation and net primary productivity (Castellanos-Barliza and Leon-Pelaez 2023).

Based on the observed levels of BC, the rehabilitated sites were deemed capable of withstanding the impacts of soil erosion via the interactions of various mechanisms involving the plant canopy, vegetation litter and roots as explained by Mendez and Maier (2008), Vatandaslar and Yavuz (2017), Lee et al. (2018), Liu et al. (2021) and He et al. (2022). Taken together, these interactions increase the resilience of rehabilitated sites, which ultimately enable them to better withstand pressures that come with post-rehabilitation land uses, such as grazing (Huruba et al. 2018).

PVCSs

In A (7), A (30) and C (10), PVCSs were 44–58% and 49–60% at HA and HC (respectively). In the rest of the sites, values exceeded 60%. According to Nsibande and Nkosi (2023), a veld is said to be in poor condition when PVCSs are 0–39%, in moderate condition when PVCSs are 40–60% and in good/excellent condition when PVCSs are ≥ 60–100%. Based on this classification, all study sites were thought to be in moderate to excellent condition, which is indicative of high capability to resist soil erosion. An excellent condition is also suggestive of a great potential to produce forage for sustained optimum livestock production (Hardy et al. 1999). As already highlighted, given that pasture establishment is usually the targeted end land use option in the Mpumalanga province, high forage production potential is an important outcome because forage quantity is the primary factor limiting ruminant production (Minson 1990).

Between all mines, excellent PVCSs were observed in mine B at both harvests. This was attributed to higher biomass production, slightly favourable soil pH, deeper penetrable soils, and higher mean monthly rainfall in mine B, as highlighted in the Biomass production section.

Grazing capacity

Grazing capacity was slightly higher in mine B (2.7–3 ha LSU^{-1}) than in mines A (2.8–3.6 ha LSU^{-1}) and C (2.8–3.5 ha LSU^{-1}). This was thought to be indicative of the fact that, at the time of this study, it would take slightly less amount of land in mine B to maintain one mature livestock unit for a year, than it would in mines A and C. The slightly higher grazing capacity in mine B was attributed to a number of factors including a thicker cover soil depth, favourable pH and slightly higher levels of macronutrients in mine B than in mines A and C, as already highlighted in preceding sections.

Notably, grazing capacity across all sites at both harvests ranged from 2.7 to 3.6 ha LSU^{-1}. This was quite an important outcome considering the fact that grazing capacity in undisturbed land in the Mpumalanga province is estimated at 3–4 ha LSU^{-1} (Dannhauser 2021). Even after reclamation, mine soils are still regarded as pedogenically young reformed systems with altered soil physical and chemical properties, which are still developing from mixtures of fragmented and pulverized rock material (Zhang et al. 2016; Stutler et al. 2022). According to Bohrer et al. (2017), such soils are likely to take decades before acceptable conditions are reached. Therefore, to observe slightly higher grazing capacity in rehabilitated sites, within a short period of 4–30 years, than in undisturbed soils, underscores the positive influence of rehabilitation efforts.

Limitations of the study

The results of this study are based on data gathered over three different seasons within a period of one year. The short duration of the study was due to limited post-doctoral research funding that was meant to cover a period of only two years. Had there been adequate funding without time constraints, data could have been collected over two or three seasonal intervals, which might have assisted us to reach more comprehensive conclusions.

The absence of adequate inflorescence in the cold-dry season complicated attempts to identify plant species. As a result, it was not possible to assess BC, PVCSs, grazing capacity and ecological status abundance at HB. Further, some sites were affected by winter veld fire in the cold-dry season. Consequently, the condition of pastures could not be fully assessed and/or compared over the three seasons within one year, as initially intended.

Conclusion

This study set out to investigate the feasibility of cattle grazing on rehabilitated surface coal mines in the Mpumalanga province. This was achieved by assessing soil physicochemical conditions and their influence on plant growth.

According to the obtained results, soil conditions were generally suitable for plant growth. In most sites, penetrable soil depth was $\geq$ 30 cm, and was deemed capable of supporting key interactions between various soil conditions that drive plant growth. In mines A and C, pH was strongly acidic ($<$ 5.5), but slightly acidic (5.8–6.4) in mine B. However, it would appear that pH did not adversely affect nutrient availability, as evidenced by medium to optimum levels of P, K, Ca and Mg in most sites. This could have positively influenced the appreciable biomass production that was observed in all sites. BC in this study was higher (36–91%) than both the currently accepted range (30–40%) for a veld in good condition in South Africa and the established target of 15% for the Mpumalanga coalfields. An adequate BC is a key indicator of a veld that is able to withstand the impacts of soil erosion. Most sites were dominated by decreaser species with PVCSs that ranged from 44% to 75%. These outcomes were indicative of pastures in moderate to excellent condition with good grazing and high forage production potential. As a result of the above conditions, grazing capacity in the studied sites was slightly higher (2.7–3.6 ha LSU^{-1}) than that of undisturbed land in the Mpumalanga province (3–4 ha LSU^{-1}).

Based on these results, this study recommends the implementation of controlled cattle grazing in rehabilitated surface coal mined lands in the Mpumalanga province. Bearing in mind the inability of mining companies to maintain optimum soil nutrient levels, cattle grazing may not only benefit livestock farmers but could also continuously improve soil conditions. A large proportion of the nutrients ingested by grazing animals are returned to the pasture in dung and urine, which contain many ingredients necessary for plant growth, including N, P and K (Gertenbach et al. 2001). However, to avoid problems associated with grazing (e.g. soil erosion), specific plans for grazing should be informed by further research aimed at determining optimum stocking rates. Further, soils previously affected by mining operations have been linked with elevated levels of potentially toxic elements. Therefore, since the re-establishment of grazing land is the present focus of mining companies in the Mpumalanga province, further investigations to ascertain metal concentrations in rehabilitation plants should be undertaken. This may assist in avoiding the possibility of the transfer of toxic elements to humans through the consumption of animal products, such as meat and milk.

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ORCID iDS

Emmanuel Cele — https://orcid.org/0000-0002-1700-1582
Monde Rapiya — https://orcid.org/0000-0002-3312-1808
Wayne Sanders — https://orcid.org/0000-0002-7927-4535
Wayne Truter — https://orcid.org/0000-0001-7701-3481

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