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From rehabilitation to restoration: a 12-year case study

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Abstract

Mine-related and post-mining disturbances have the potential to persist almost indefinitely and can cause ongoing habitat deterioration and fragmentation. This, in turn, can lead to irreversible declines in critical ecosystem functions, directly affecting the natural environment and communities that depend on it for economic activities and basic human needs.

We have been tracking the development of post-mining restoration efforts on a platinum mine for the past 12 years, and our findings have been used to guide the maintenance actions required to sustain ecosystem recovery trajectories. The monitoring framework is extensive and covers landform recreation, soil hydrology and physics, soil chemistry and microbial activity, vegetation dynamics and recolonisation of rehabilitating sites by birds, mammals, reptiles and amphibians.

In this paper we delve into showing how the original rehabilitation-focused planning transformed into a restoration mindset. Shifts in ecosystem resilience following droughts, fires and intensive grazing, as well as social expectations (the majority of the site is within the Marikana Thornveld vegetation type, recently uplisted to endangered status), have required ongoing planning and management responses.

The ecosystem responses to post-disturbance ecological development have shown improving trends across 12 years of monitoring, with stochastic deviations from trends observed for different taxa under varying prevailing conditions. The long-term nature of the monitoring program has proven its value in that it has allowed for high-confidence trend analyses that inform restoration planning and maintenance activities.

Whilst restoration efforts have not necessarily been perfectly executed, and external ecosystem stressors have hampered consistent ecosystem development, this study shows the importance of undertaking rehabilitation and restoration activities within a clear framework that is outcomes-oriented and data-driven.

Keywords: *mine rehabilitation, ecosystem development, restoration, monitoring*

1 Introduction

The post-mining ecosystem recovery paradigm is often confusing, with a variety of terms being used to describe post-mining efforts. Each comes with a diversity of definitions which influence perceived inputs and outcomes. Approaches can vary from reclamation through to rehabilitation and all the way to restoration (Lima et al. 2016).

The final rehabilitation (as an umbrella term) approach should be guided by the biogeoclimatic constraints and considerations of post-mining land-use (PMLU) requirements, in the context of social expectations and regulatory requirements. This makes rehabilitation a very site-specific undertaking.

In broad terms, attaining the highest level of land capability is preferred (Mentis 2019) as it allows for the greatest range of potential PMLUs and should, if executed correctly, result in the lowest residual and latent environmental impacts going forward. Mining companies and rehabilitation/restoration practitioners should, ideally, have a strategy that can be followed from the outset but that has sufficient versatility to pivot should

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mining methods, advancements in reclamation technology, regulatory frameworks or community expectations change over time.

Attaining the requisite land capability and tracking ecosystem recovery post-mining is best undertaken via a dedicated and cross-disciplinary monitoring framework that considers all aspects of rehabilitation, from geotechnical aspects through to land forming and surface water controls, groundwater management, surface stability and erosion, substrate chemistry and microbiology, and habitat creation and colonisation by fauna and flora (Mentis 2019). Developing and maintaining such a monitoring framework and tracking development trends over time to prove attainment of agreed relinquishment criteria remains the best means of both proving rehabilitation outcomes and providing information on maintenance requirements and interventions required to prevent degradation. We have seen a substantial gap in overall expenditure and rehabilitation performance between mines that invest in active rehabilitation monitoring and maintenance and mines that do not (Haagner et al. 2025). Furthermore, gaining economic data on implemented PMLUs and tracking these yield/productivity trends over time is also a powerful means of proving the financial case study for sustainability and circularity that is required in many mining jurisdictions (Lèbre et al. 2017).

2 Study background

2.1 Study site

The study site is situated in the Rustenburg district of the western limb of South Africa's Bushveld Igneous Complex, an area rich in platinum group metals (Figure 1). The mine has a mineral lease of >30,000 ha and is located within the former Bophuthatswana homeland. Mining for platinum has been ongoing here since the 1960s (Bannon 2013). The landscape is dominated by an industrial-rural matrix of platinum and chrome mines and peri-urban housing and subsistence agriculture (particularly extensive livestock grazing), with extensive degraded and transformed areas.

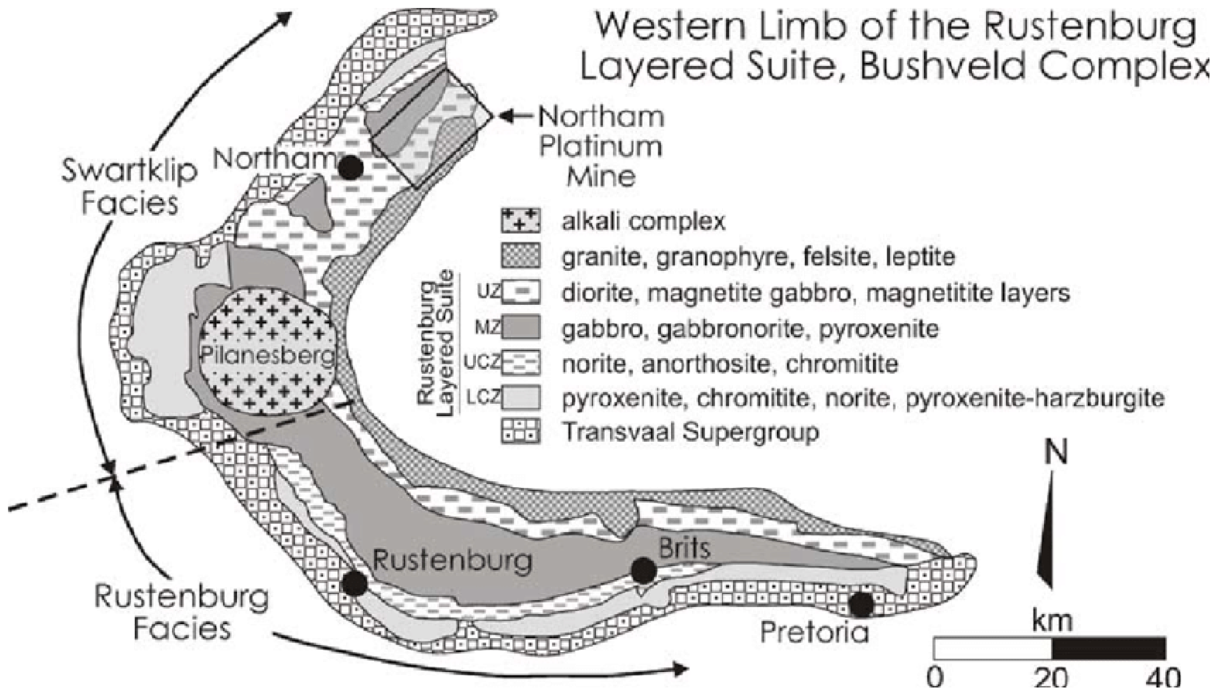

Figure 1 Map of the western limb of the Bushveld Igneous Complex, in which the study area is situated (Roberts et al. 2007)

2.2 Climate

The region currently experiences a summer rainfall regime. The highest precipitation occurs between November and March, with an average precipitation above 90 mm. Average annual precipitation over the past 27 years is calculated as 615.2 mm. Figure 2 shows the annual rainfall for this period. The open cast rehabilitation surveys started in the 2012–2013 rainfall season, which was below the 27-year average. From 2011 to 2020 a trend of two years with below-average rainfall followed by one year of above-average rainfall can be seen. In this regard, the 2014–2015 season had the lowest rainfall in the past 27 years. The past four years had rainfall in line with the 27-year average, providing a prolonged respite from the drought conditions from 2017 to 2019. The highest average maximum temperatures were 34°C (February 2022) and 33°C (December, March and October 2019, and November 2021) and the lowest average minimum was 7°C (July 2018–2021 and 2023). The average temperatures during the 2024 assessment period ranged between an average low of 20°C and an average high of 31°C.

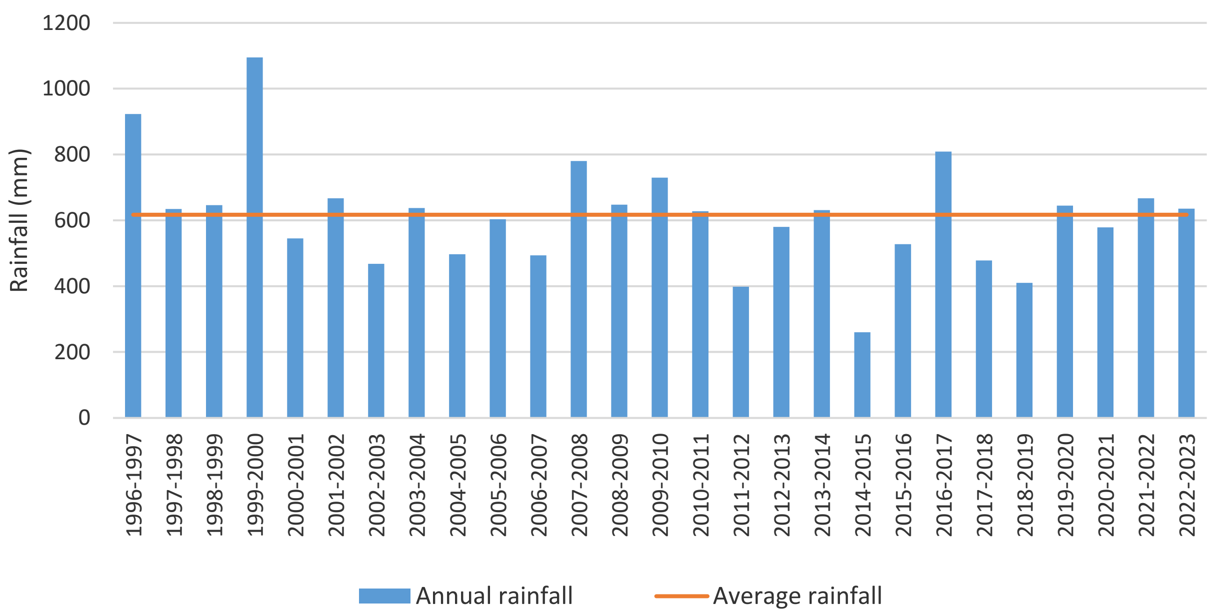

Figure 2 Annual and long-term average rainfall for the study site over a 27-year period

2.3 Geology and soils

The geology of the lease area is rather uniform, consisting almost entirely of anorthosites and norites of the Rustenburg Layered Suite within the broader Bushveld Igneous Complex.

Deep Arcadia soil forms dominated the pre-mining environment, accounting for over 80% of the surface area. The soils generally had an effective depth of >900 mm and were best suited to grazing and very low-intensity dryland permaculture. Rensburg was the subdominant soil form (shallower and in wetter regions), with some Shortlands and Hutton (red) soil forms evident in intrusions.

The predominant visible soil forms are thus of the swelling, dark Vertisol clays (very high clay content of >40–70%). These soils have very high inherent fertility with cation exchange capacity (CEC) values in the region of 45–50 cmol/kg but have complex structural problems which limits their potential for cultivation.

2.4 Vegetation

The general floristic and phytosociological associations are that of open *Vachellia (V) karroo* (previously *Acacia karroo*) woodland. There have been various vegetation classifications for this region but, for the purposes of this study, the most recent one of Mucina & Rutherford (2006) will be followed. They have classified it as belonging mostly to SvCb 6 Savanna (Marikana Thornveld), and it is registered as an endangered habitat type in need of protection (Government of South Africa 2022).

V. karroo is the dominant woody species, with sub-dominance of *Senegalia caffra* (*A. caffra*), *V. gerrardii* (*A. gerrardii*), *V. tenuispina* (*A. tenuispina*), *Searsia lancea*, *Combretum molle* and *Ziziphus mucronata*. The shrub layer is dominated by *Olea europaea* subspecies *africana* and *Searsia pyroides*. The herbaceous layer consists of mostly *Eragrostis lehmanniana*, *Elionurus muticus*, *Themeda triandra*, *Setaria sphacelata*, *Hermannia depressa*, *Ipomoea obscura*, *Heteropogon contortus*, *Fingerhuthia africana*, *Hyperthelia dissoluta* and *Pogonarthria squarrosa*.

3 Materials and methods

The first rehabilitation works for the open cast mined areas was initiated in 2000 and was concurrently undertaken as pits have been closed, extending up until 2013. The total area under open pit rehabilitation spans 401 ha across 28 separate open pits that ranged in size from 0.82 to 68.40 ha. The rehabilitation process consisted largely of shaping landforms to a whale-back landscape over the pit to allow for expected settling back to original ground levels (OGLs) and then topsoiling these with live-stripped topsoil in a roll-over process. The topsoil was considered to contain sufficient seed banks, and no physical or chemical amelioration was undertaken. The monitoring framework was developed in 2012, once most rehabilitation activities had been completed. The monitoring framework was based on the process hierarchy of first signing off on geotechnical and landform considerations, then progressing to groundwater risks and then surface rehabilitation. The rehabilitation hierarchy for assessment is shown in Figure 3 below. For the sake of brevity, only the surface rehabilitation monitoring methods will be described below.

The monitoring program for surface rehabilitation comprised 133 fixed points that were monitored annually from 2013–2024. A further set of analogue sites was also monitored, which comprised seven relatively undisturbed reference points, as well as three spontaneously regenerating sites that were disturbed by factors other than mining and where rehabilitation had been unaided and thus represented natural ecosystem regeneration rates. Substrate physico-chemistry was typically analysed in the first year of monitoring as it is considered stable. Landscape function and ecosystem development were monitored annually and terrestrial biodiversity was monitored biannually in summer and winter to represent the different biotic assemblages of mobile species.

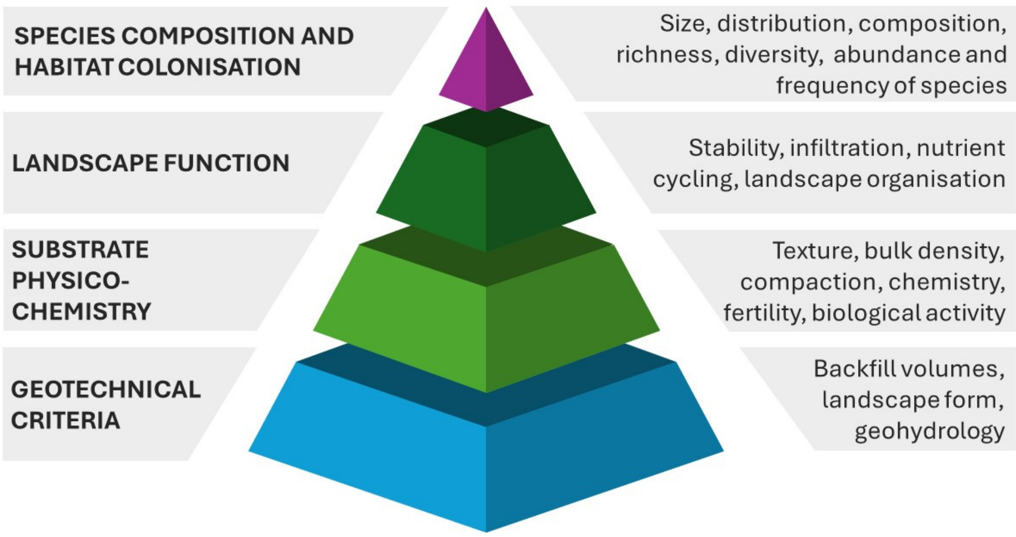

Figure 3 The rehabilitation hierarchy informing the rehabilitation monitoring framework for the study site (adapted from Haagner et al. 2025)

3.1 Substrate physico-chemistry

At each of the 133 fixed monitoring points, soil samples were collected at a subset of depths and characterised for chemical risks (acidity/alkalinity, salinity, exchangeable sodium percentage (ESP) and plant-available heavy metals), substrate fertility (pH, electrical conductivity (EC), macronutrients and

Walkley-Black organic carbon) and physical properties (7-fraction textural analysis, dry bulk density, compaction and foundation indicators).

3.2 Ecosystem development (landscape function)

Once the geotechnical sign-off was achieved and the substrate physico-chemistry found to have no inherent or latent risks, each of the rehabilitating and reference sites were annually assessed for landscape function using landscape function analysis (Tongway & Hindley 2004). The method has been well described for this site (Haagner & Malo 2014) but broadly encompasses utilising indicator-based field assessments to score various subcriteria to inform three emerging landscape function indices: namely stability, infiltration and nutrient cycling.

3.3 Terrestrial biodiversity monitoring

In addition to the vegetation characterisation undertaken as part of the landscape function assessments, which focus on dominant species and vegetation structure, additional vegetation diversity assessments were undertaken to focus on rarer species whose colonisation was important in the context of the endangered ecosystem status, at a subset of representative rehabilitating pits of different ages. Vegetation diversity assessments were undertaken annually.

For the faunal assemblage monitoring, focal taxa were birds, reptiles, amphibians and mammals. Birds and mammals were monitored biannually (summer and winter) at fixed points due to their mobility and seasonal variation in community structure, whereas reptiles and amphibians were monitored annually during peak rainfall periods. These were all undertaken at appropriate fixed locations across the rehabilitating open cast pits and at unmined reference sites.

3.4 Land capability and land use

The mine's environmental management program and mine closure plan list extensive livestock grazing as the preferred end land use. Hence the vegetation monitoring data from the rehabilitating open cast pits were utilised to calculate grazing capacity as an indicator of post-mining landscape productivity. These were then compared to regional data and data from unmined reference sites. The extent of livestock grazing and the frequency and intensity of wildfires were also recorded. Actual stocking rates of grazing animals could not be recorded as the areas are under tribal authority and are thus open for all the community to bring livestock to for grazing as required.

4 Results and discussion

4.1 Geotechnical sign-off, landform and groundwater considerations

4.1.1 Geotechnical and landform considerations

The total void volumes were taken from survey data and correlated with ore, waste rock and topsoil volumes to create a materials balance that was further used to identify whether the correct settling rates and bulking factors had been applied in the final landform designs. Annual analyses of the survey data showed that of the 28 pits, the 26 well-designed and constructed ones did sag back to OGL. The remaining two pits showed discrepancies where excess waste rock was returned to the pits, resulting in post-mining landforms that were not expected to settle back to the OGL over time. One of these pits showed no sagging and remains at unsuitable slope geometry (considering the high erodibility of the soils), whilst the remaining pit underwent differential settlement that resulted in a pocked landform that had to be levelled.

Hence 27 of the pits have now achieved geotechnical and landform sign-off as they have settled to OGL, blend in with the surrounding flat topography and have no run-on/run-off constraints. The remaining pit with unsuitably steep and long slopes is being monitored and revegetation is underway to evaluate whether erosion can be kept in check with improved vegetation cover.

4.1.2 Groundwater considerations

The mine undertakes quarterly groundwater quality sampling and biannual borehole yield sampling. As anticipated, the backfilled pits have become underground reservoirs and water levels have largely rebounded and are maintained at pre-mining levels. The groundwater quality showed elevated salinity (due to geological influences) and nitrate levels (presumed to be from blasting residues), although the nitrate trends showed declines over time that are thought to be due to organic processes. All other monitoring criteria were in line with prescribed limits.

No decant has taken place and nor is any predicted. There are no groundwater users with boreholes in the affected aquifers and water qualities conform to the regional livestock watering standards; hence the groundwater considerations have been signed off on, although monitoring will continue to and beyond closure.

4.2 Physico-chemical substrate conditions

4.2.1 Substrate physical properties

Although some mixing of the topsoils and subsoils took place during soil stripping (single strips of 1.2 m), the replaced soils are fairly uniform due to the self-mulching nature of the Vertisol clays. This further renders them friable and not prone to compaction. The soil textural gradings showed low variation from the pre-mining reference conditions (Figure 4), indicating good potential for rehabilitation. Soil permeabilities are generally very low in Vertisols. The soil compaction measurements were suitably low, as expected from self-mulching clays. Together with texture, these influence soil permeability, which showed some differences between unmined and rehabilitation sites. However, only the youngest rehabilitation showed substantially lower rates (Figure 5). This is considered, in part, due to the lower vegetation cover in younger sites, particularly woody plant cover, and should be tracked further over time, with interventions possibly being required in future.

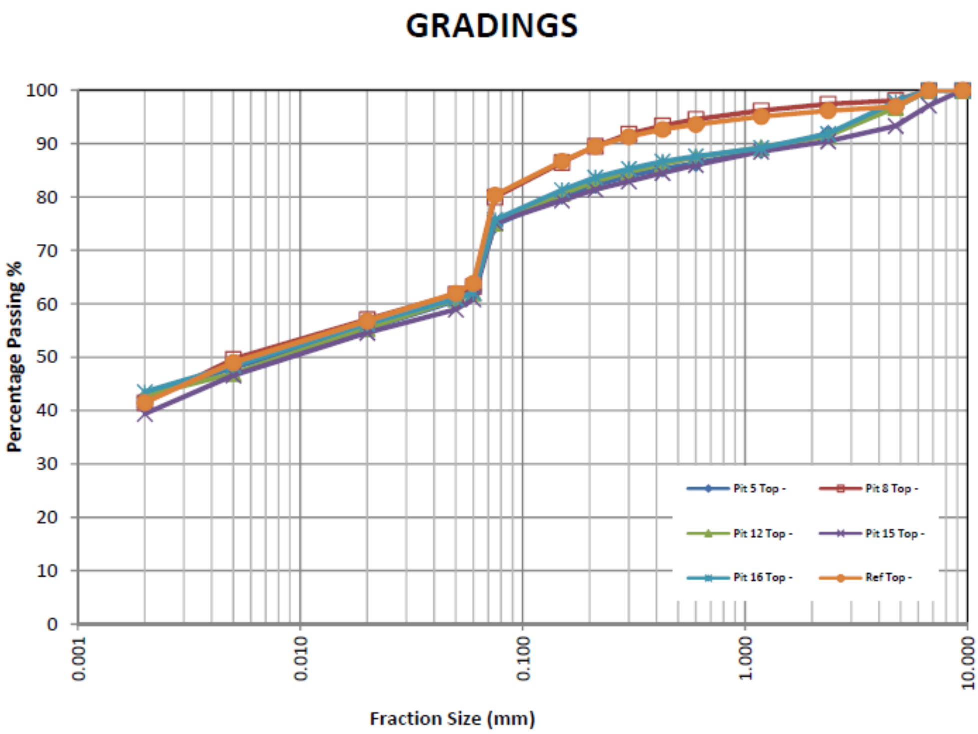

Figure 4 Soil textural gradings of a selection of rehabilitating open pit soils compared to unmined reference soils

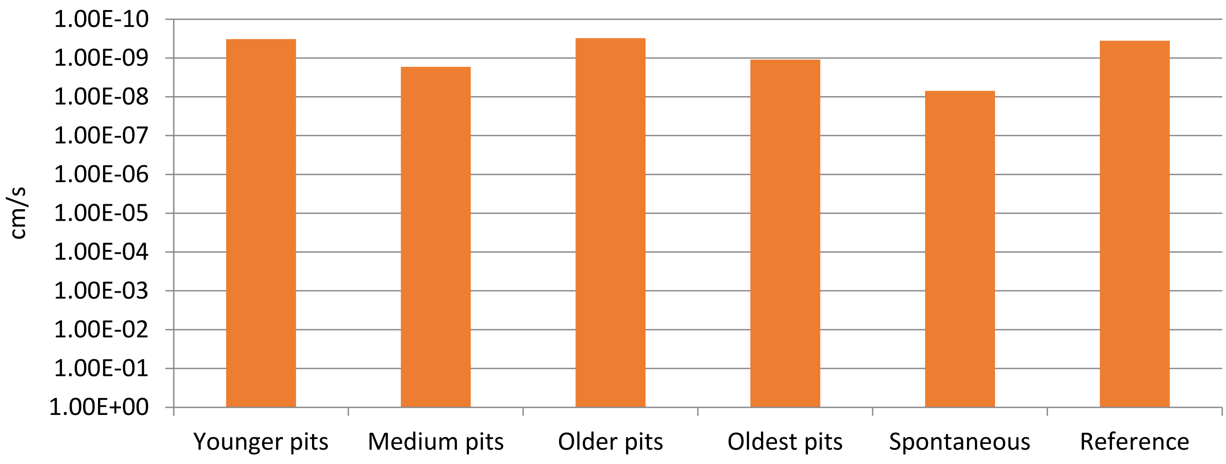

Figure 5 Permeabilities for a selection of rehabilitating open pit soils compared to unmined reference soils

4.2.2 Substrate chemical properties

The soil chemical analyses typically showed relatively uniform characteristics that did not change significantly with depth, largely due to the self-mulching nature of the Vertisols. The substate pH was always alkaline (pH range 7.1–7.7) with low salinity (EC range 17–114 mS/m), with very high fertility (CEC of >21–32 cmol/kg) and reasonable organic carbon (0.93–2.11%). These values are all in line with the unmined reference site data, although CEC is slightly lower in rehabilitation sites. Sodium (Na), and particularly ESP, was an outlier. Na concentrations in unmined reference areas were very low (< 9 mg/kg), as was the ESP (0.1%), whereas in some rehabilitating pits the Na concentrations were up to 700 mg/kg, translating to >11% ESP. Whilst this is a risk factor, it is only expected to manifest in physical risks on sloped areas where erosion could occur. Fortunately, the areas with elevated ESP are actually in slightly depressed areas, which may also contribute to the higher Na concentrations in these areas.

The full chemistry datasets are too extensive for the format of this publication. For reference, the macronutrient cation concentrations for a range of the rehabilitating open pits and reference sites are shown below in Figure 6 and represent the upper (0–300 mm) and lower (300–800 mm) soil horizons.

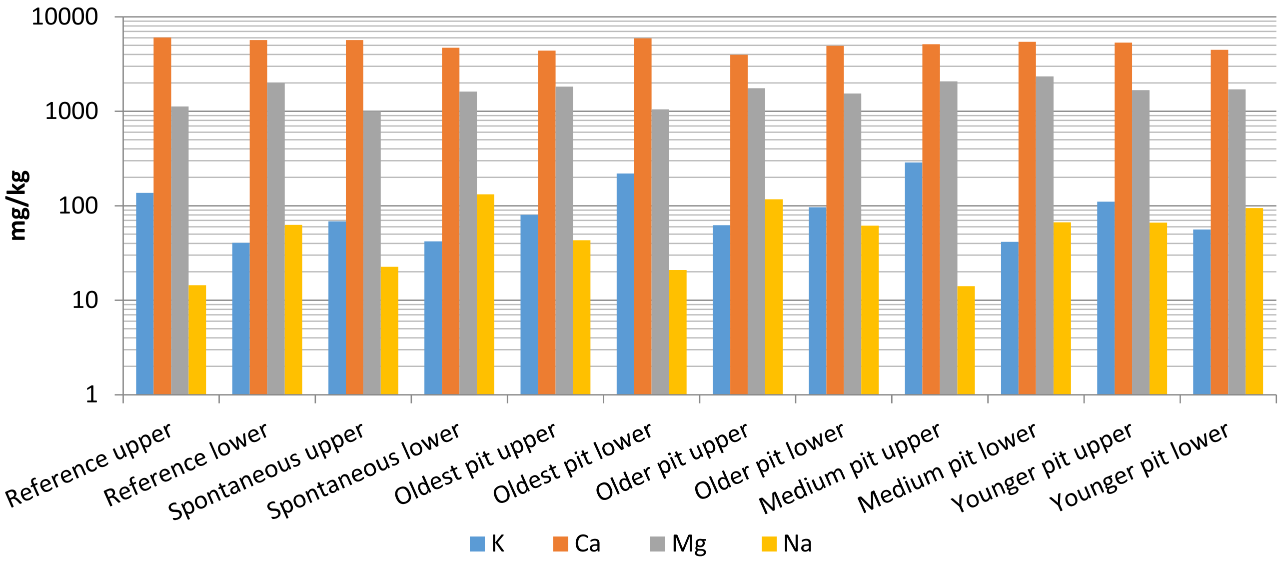

Figure 6 Basic plant nutrient levels of soil samples from rehabilitating pits compared to those from unmined reference sites

4.3 Ecosystem development and landscape function

The landscape function analysis data are presented here, first for the landscape organisation index (LOI), a measure of describing the proportions of self-arranged biotic and abiotic functional ‘patches’ (landscape elements that capture and recycle mobile resources such as topsoil, seed, runoff and litter), such as plants, roots, debris and depressions versus dysfunctional ‘interpatches’ (where mobile resources are lost from the system), which are typically bare areas. As an example of the larger dataset, the LOI for the older rehabilitating pits (18–24 years post-rehabilitation) is shown in Figure 7. A LOI score of 1 indicates 100% dominance by patches. All of the older rehabilitating pits show the same trend of higher baseline scores from 2013, followed by a series of reduced scores from 2014–2019, followed by a substantial recovery, mostly to above baseline scores, in 2021–2024. This reflects the responses to rainfall, as Figure 2 shows that 2014–2019 typically had well below-average rainfall (and drought conditions from 2014–2016 and again 2017–2019). Whilst these declining trends were concerning at the time, the dramatic increases in LOI once the rainfall returned to above-average conditions showed ecosystem resilience, confirmed by the same trends observed in the reference sites. Although the actual LOI scores for some of the rehabilitation pits are at lower levels than the unmined reference sites, the response trends are considered very positive and indicative of functional rehabilitating landscapes, albeit often at lower levels of function when compared to the unmined situation.

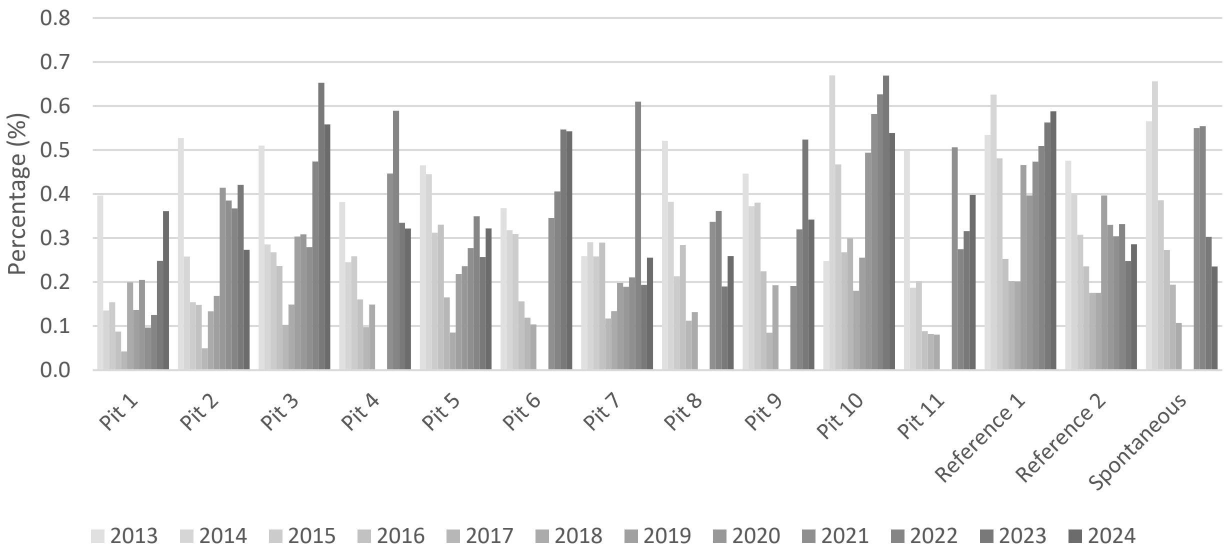

Figure 7 Comparison of landscape organisational index between rehabilitating pits from 2013–2024

Delving deeper into the data for comparisons between rehabilitating pits and unmined reference sites, Figure 8 shows the trends in relative abundance values for the different patch and interpatch types from 2013–2024, whilst Figure 9 shows the trends for rehabilitating open pits. The trend for unmined reference sites shows that graminoid-dominated patches outnumbered interpatches during 2013 and 2014, whereafter declines were prevalent during the ensuing drought years but have since recovered to near-baseline conditions. Whilst interpatches have dominated in the rehabilitating sites, the same trend has emerged, and the same resilience patterns in the same magnitude are observed as for the reference sites; indeed, interpatch prevalence is the same in the reference sites as in the rehabilitating sites. The contributions of abiotic patches have remained static (and at low levels), further supporting the conclusions drawn that the resilience is in response to prevailing rainfall conditions. Lastly, the prevalence of woody patches has increased over time in both the reference and rehabilitating sites and currently sits at comparable levels.

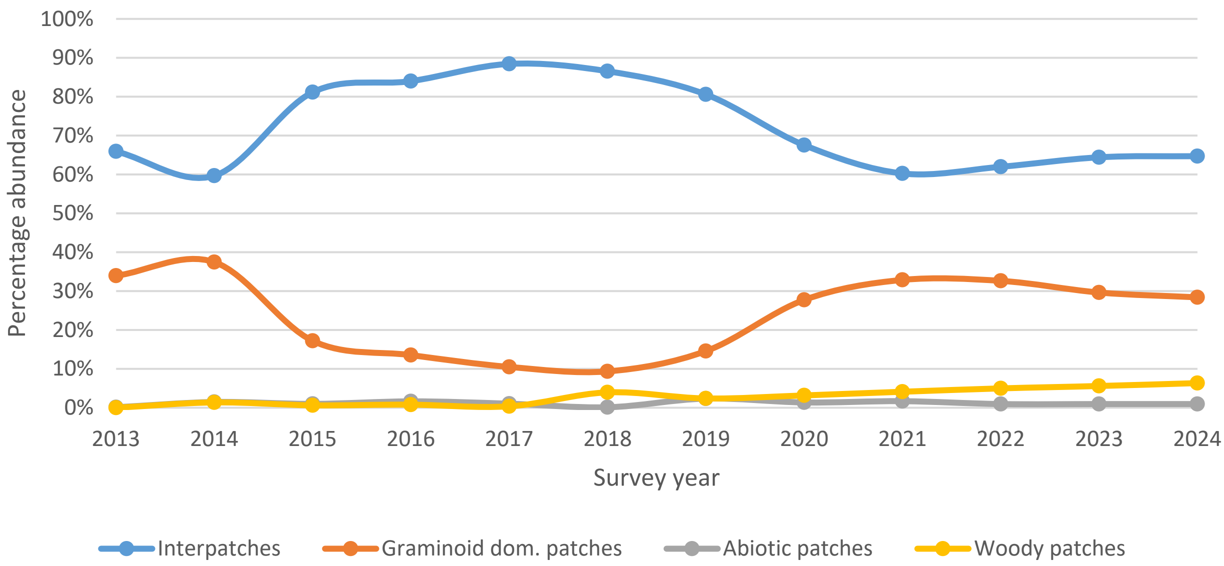

Figure 8 Relative abundance of patch/interpatch types in unmined reference sites

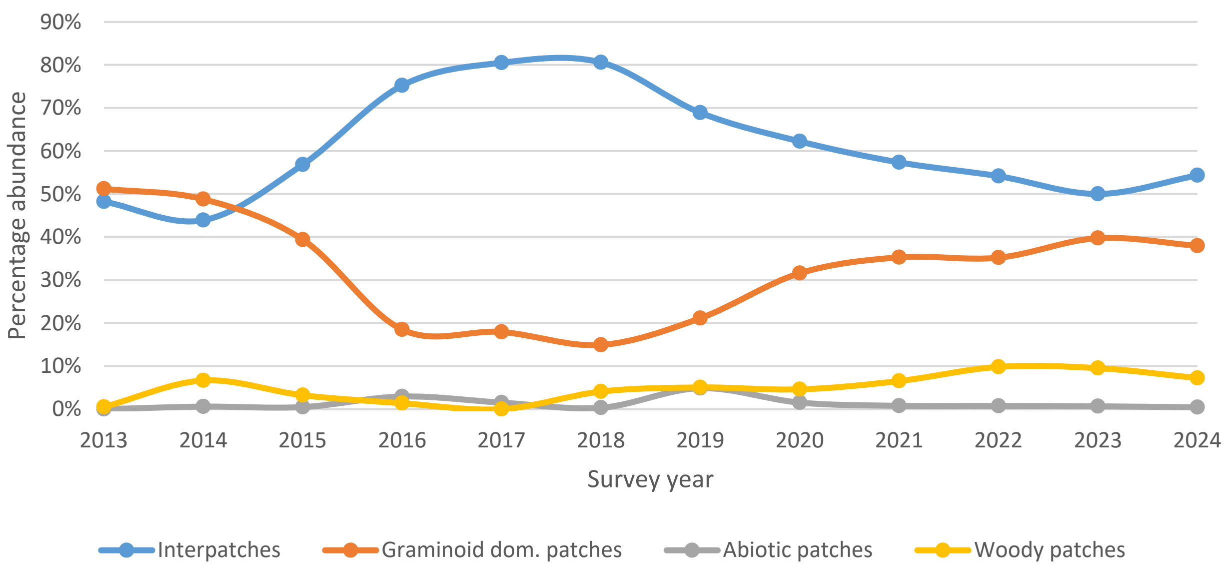

Figure 9 Relative abundance of patch/interpatch types in rehabilitating open pit sites

Considering the emerging overall landscape function scores (comprised by totalling the infiltration, stability and nutrient cycling index scores) shown in Figure 10, the initial assessment period (2013–2016) typically showed comparable levels of function between rehabilitating pits and reference sites. These then declined in the rehabilitating sites (stable in the reference sites) during the intermediate drought periods but increased dramatically in all sites when rainfall levels returned to average/above-average conditions. Whilst the reference sites did show greater resistance to drought conditions, the resilience trends were extremely encouraging, with some rehabilitating pits performing at similar or better levels than the reference sites; all but one fell above the critical threshold, indicating intervention requirements.

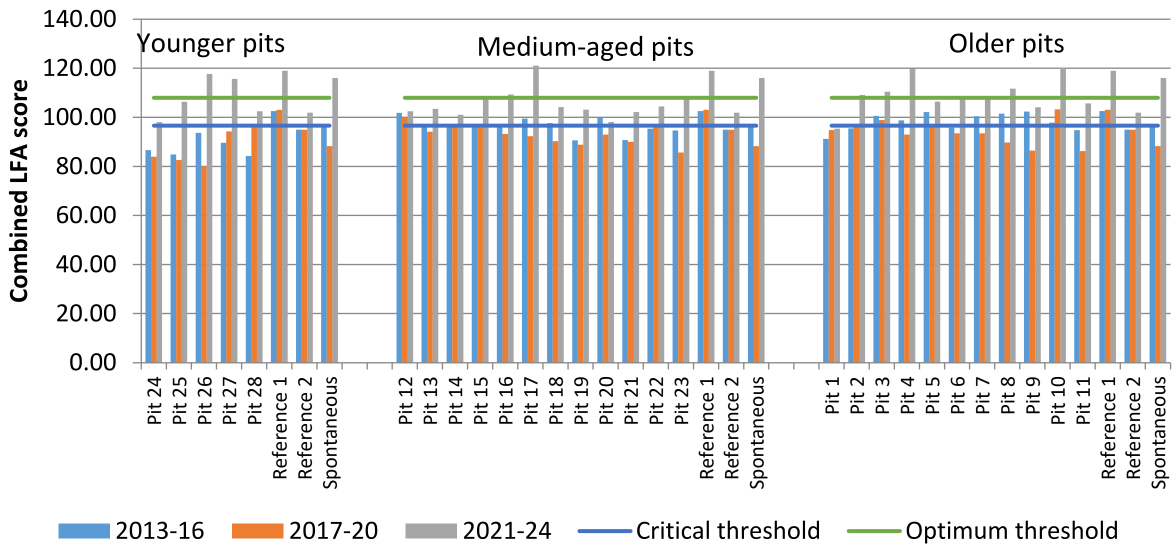

Figure 10 Comparison of overall landscape function assessment scores for older rehabilitating pits and unmined reference sites

Figure 11 indicates the changes in vegetation dominance (split by vegetation growth form and successional state) for a subset of the data. Despite the encouraging trends described for overall landscape function, the vegetation composition shows that there has been an overall decline in the desirable climax grasses at the rehabilitating and reference sites, which have been replaced with pioneer grasses and forbs. This does indicate that the maturity of all sites is still in development and suggests a negative response to uncontrolled grazing pressures that were sustained even throughout the drought periods. The older rehabilitation showed the greatest displacement of climax grasses, whilst the younger rehabilitation showed lesser displacement.

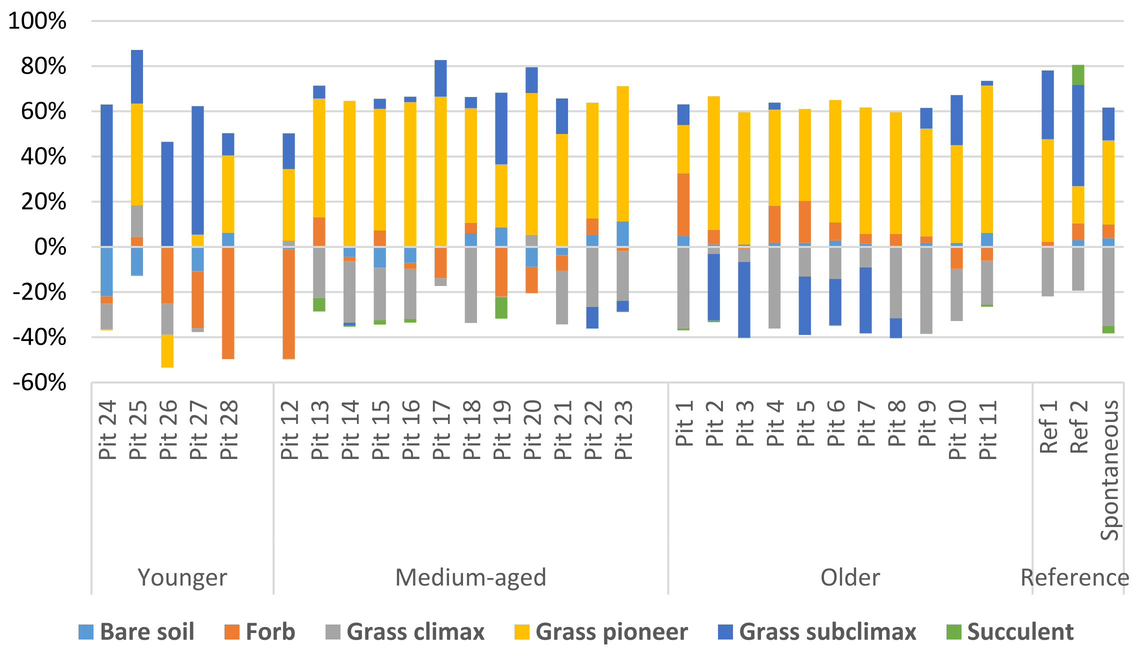

Figure 11 Changes in vegetation dominance over time from baseline to current conditions

4.4 Terrestrial biodiversity and habitat colonisation

Unfortunately, in a brief paper of this nature, the full terrestrial monitoring datasets cannot be adequately displayed. Two subsets, the amphibian and avifaunal data, are presented here with brief descriptions of the reptile and mammal data. Figure 12 shows the trends in amphibian community changes over time (no data for 2020 as nocturnal surveys were restricted as a result of the COVID-19 pandemic). The mean amphibian species richness and abundance has increased since monitoring began and (although fluctuating during different rainfall periods, as expected) has peaked at current levels, whereas analogue sites have remained constant. This is a very positive trend for rehabilitation and habitat colonisation by important niche communities and rehabilitating sites now have comparable levels to analogue sites.

For the avifaunal community, the Shannon–Wiener diversity index scores are shown (Figure 13) as the data better lends itself to diversity descriptions which incorporate both abundance and species richness. Whilst the trends for avifaunal diversity varied slightly during initial monitoring periods (typically below reference site levels), this has increased since 2021 and for the past two years the rehabilitating sites show greater avifaunal diversity scores than the reference sites. This is also a significantly positive indicator for rehabilitation success and habitat colonisation as birds are highly mobile (especially migratory species) and the results show that their resource requirements are met by rehabilitating sites at levels comparable to the unmined reference sites.

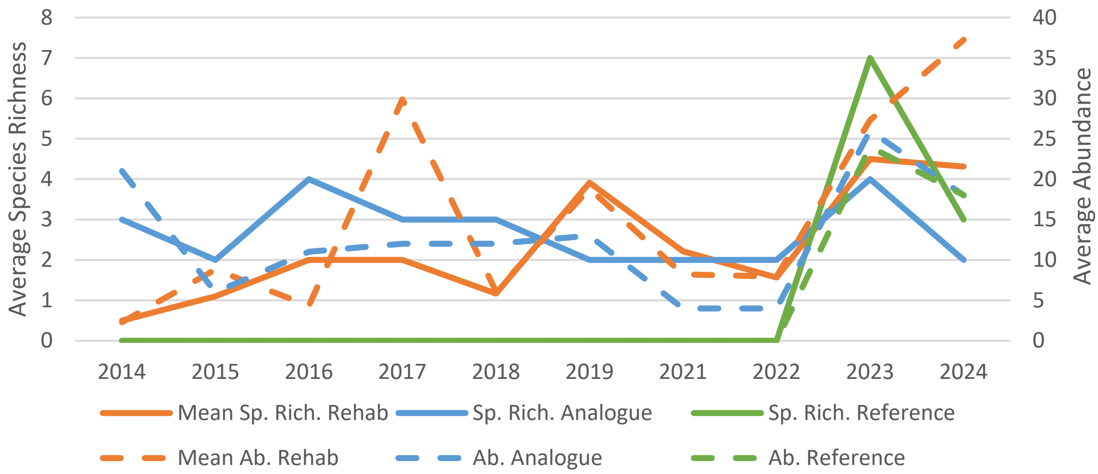

Figure 12 Amphibian community trends for the rehabilitating and reference sites from 2014–2024

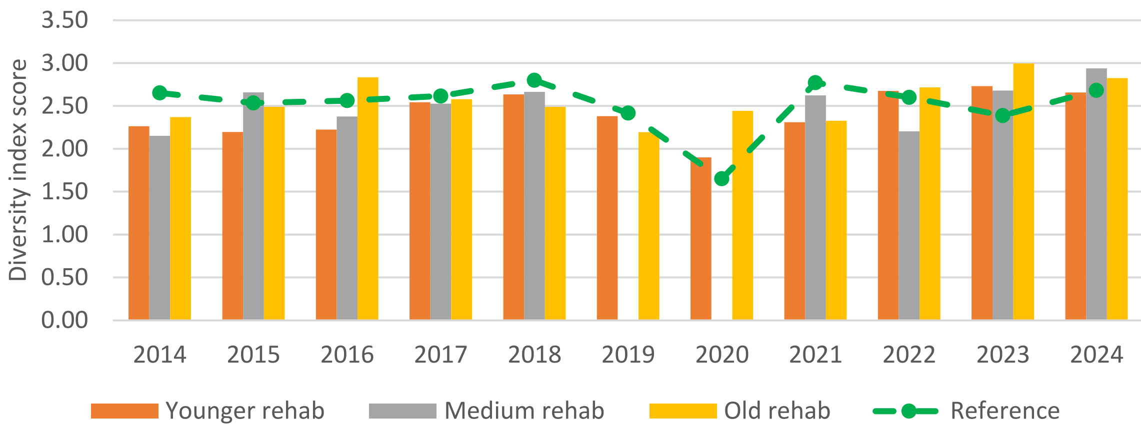

Figure 13 Avifaunal community trends for the rehabilitating and reference sites from 2014–2024

The trends for the reptile community are not as positive as sharp declines have been observed at rehabilitating and reference sites, indicative of broader ecological trends. The overall community structure has shown that mammals' species richness and abundance are stable to slightly increasing over time at rehabilitating sites, albeit at lower levels than at reference sites (which have remained stable over time); thought to be indicative of higher levels of persecution in the more accessible rehabilitating sites.

5 Conclusion

Given the positive signs in ecosystem recovery and resilience, largely comparable between the rehabilitating sites and the unmined reference sites, a decision was made by the mine to shift the focus from rehabilitation to a restoration paradigm in 2022. This coincided with the uplisting of the dominant vegetation type, Marikana Thornveld, to endangered status. This has refocused interventions from a more passive to an increasingly active approach, where legacy issues (such as landform deficiencies, ESP, invasive plant eradication and poor vegetation establishment) are now actively addressed. The gap between the poorer-performing rehabilitating sites and the unmined reference sites is now better understood on the back of 12 years of intensive monitoring data, and site-specific plans have been developed for implementation to get all rehabilitating sites to reference site levels. Hence, we use this case study to propose the following milestones for pivoting from a rehabilitation-focused to a more restoration-focused approach:

- geotechnical sign-off criteria are reached
- physico-chemical soil properties are no longer limiting and resemble analogue sites
- soil microbial function levels are approaching analogue values
- vegetation community assemblages (structure, function and composition) resemble analogue sites and show resilience to stochastic disturbances
- landscape function parameters approach and consistently exceed optimal thresholds
- key faunal assemblages show structural and compositional similarity to analogue sites
- land-use criteria (grazing capacity) are in line with regional reference values
- populations of species of conservation concern show stable trends over time.

However, some challenges do remain; specifically land stewardship, wildlife persecution, over-utilisation of grazing, over-harvesting of firewood, regional bush encroachment and unmanaged land transformation.

Acknowledgement

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