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Soil indicators for restoration monitoring in arid regions – a case study from the central Namib Desert

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ABSTRACT

Soil properties are indicators for ecological processes and thus contribute to determining "functional and self-sustaining ecosystems" in a rehabilitation context. In a recovering ecosystem these indicators are expected to follow a trend towards a benchmark. Whether such a trend can be observed in rehabilitation projects in an arid environment was the question of this study. Soil properties of restored areas with six different treatments and corresponding reference sites were analysed at Trekkopje Mine in the central Namib Desert over six years. Soil properties which were reasonably stable over the monitoring period in reference sites, and not even affected by rainfall patterns, were pH, organic carbon, calcium, potassium, magnesium and clay content. The chemical indicators were likely linked to the treatments, although clear patterns had not yet developed. Organic carbon content was, however not linked to treatment or standing biomass. The best re-vegetated sites showed the lowest organic carbon, and thus no link between standing biomass and soil organic carbon. This may indicate that factors other than standing biomass control soil organic carbon and therefore call into question its use as an indicator of soil fertility in arid, recovering ecosystems. Control, scarified and topsoil-treated sites showed a clear trend in declining calcium, possibly as a result of the exposed, initially highly calcareous subsoil and subsequent leaching. Therefore, only one short-term soil indicator was supported by this study and more time and possibly a larger sample size are needed to show trends in other soil properties. Long-term data collection which consistently applies the same monitoring protocol is therefore essential in an arid environment and longer time intervals between monitoring events (e.g. 2-3 years) can be considered, if costs need to be reduced.

Keywords: completion criteria; mining; Namib Desert; rehabilitation; soil fertility; substrate treatments

INTRODUCTION

Restoration projects often strive to provide a "functional ecosystem which is self-sustaining" (Grant & Koch 2007; McDonald *et al*. 2016). In practice this means the restored ecosystem needs to be physically and biochemically stable and support adequate biodiversity in the long term. Evaluating restoration success requires the measurement of a suite of indicators that are recommended to cover the ecosystem attributes diversity, structure and processes (Ruiz-Jaen & Aide 2005; Alday *et al*. 2011). Soil properties and soil nutrient status are therefore expected to be included in restoration monitoring programmes, as these are a measure of ecological processes taking place in a restored ecosystem (Tongway & Hindley 2004). Ecological restoration has been defined as "setting natural communities on a trajectory of recovery within the bounds of what could be expected naturally within the target area" (Society for Ecological Restoration 2005). Long-term measurements are therefore expected to show a trend towards an accepted benchmark with time, which is usually a comparable undisturbed habitat.

Despite a vast body of literature on the practice and monitoring of restored ecosystems (e.g. Whisenant 1999), including studies from arid areas (Holm *et al*. 2002; Bestelmeyer *et al*. 2006), the question of recovery time has not been adequately addressed. Ecological processes in arid areas are inherently slow (Polis 1991) and driven by pulses of rainfall (Noy-Meir 1973). Recovery can therefore be expected to take well over a century in some areas (Bolling & Walker 2000).

Mining in the central Namib Desert has intensified over the last decade and three new uranium mines have been established. Developing site-specific restoration measures is therefore crucial and evaluating these requires monitoring. The study was carried out at Orano Mining Namibia's Trekkopje mine, where a pilot project to develop appropriate rehabilitation methods was set up in 2010. Different surface treatments are being tested in these rehabilitation trials. Soil properties are one of the monitoring variables and expected to provide an indicator for ecosystem processes (Tongway & Hindley 2004; Ruiz-Jean & Aide 2005). Annual vegetation monitoring was initiated in 2011 while

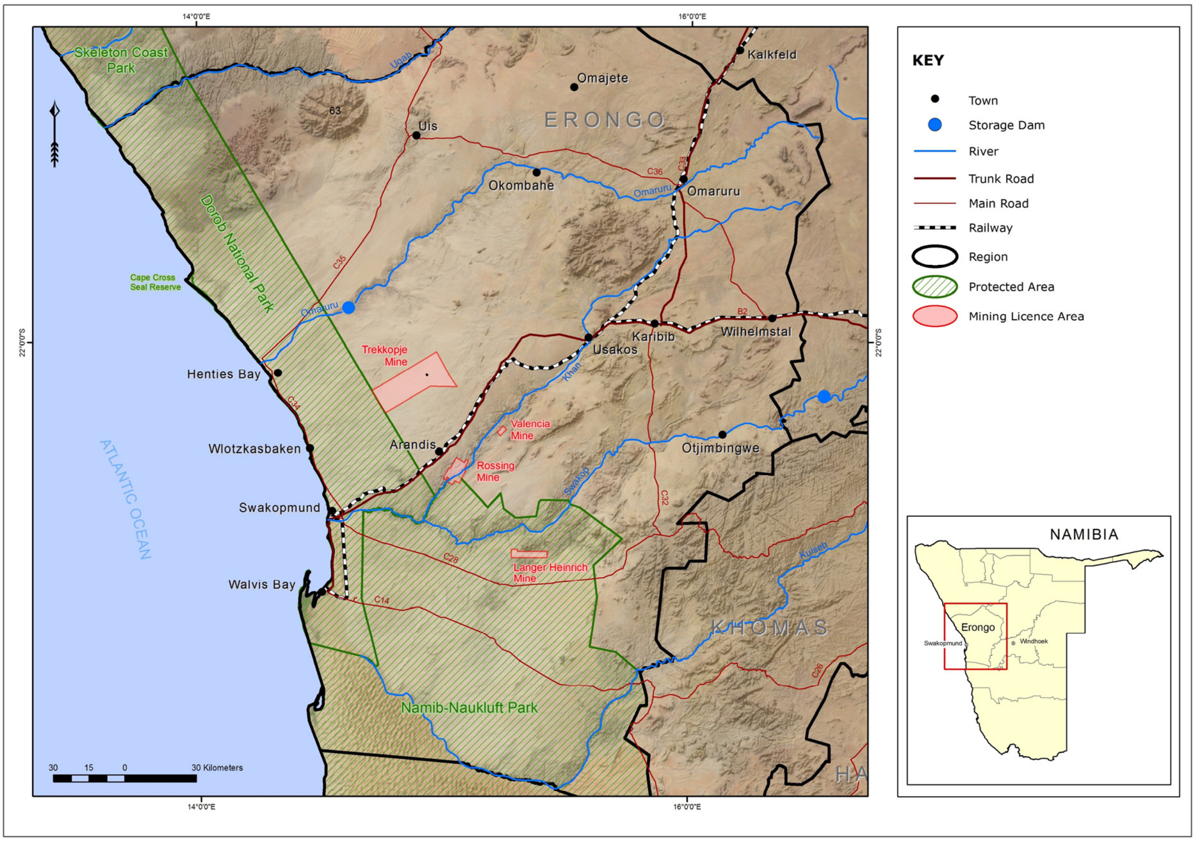

Figure 1: *Location of study area and rehabilitation trial site (• inside mining licence area) in Namibia (map credit: Orano).*

soil sampling, as described in this study, covers the monitoring period 2012-2017. This case study reports on six years of soil property monitoring.

MATERIALS AND METHODS

Study area

Orano's Trekkopje Mine is located in the central Namib Desert in Namibia. The mine is positioned on a gently sloping gravel plain at approximately 550 m altitude, some 40-60 km east of the Atlantic coast (Figure 1). It is dissected by a network of largely westwards trending, shallow, dry water courses. The vegetation comprises ephemeral grassland and dwarf shrubland, dominated by various *Stipagrostis* species. *Zygophyllum stapffii* and *Arthraerua leubnitziae* are the dominant shrubs, but perennial plant cover is largely restricted to the dry water courses and reaches no more than 20 % cover (A. Burke, pers. obs.). Ephemeral plant cover is directly linked to rainfall and in good seasons can reach up to 50 %. Soils are poorly developed calcareous calcisols and gypsisols, with saline and gypsum accumulations as well as local biological and chemical crust formation.

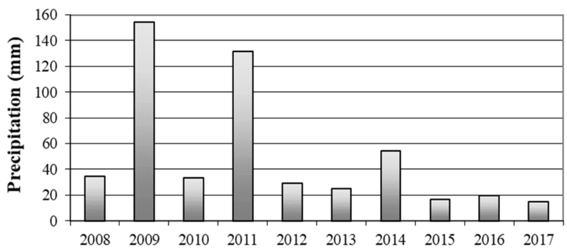

Figure 2: *Total rainfall during the rainy season October – September (e.g. 2016 comprises rain between 1st October 2015 and 30th September 2016) at Trekkopje Mine in the central Namib Desert.*

Mean annual rainfall in the study area was modelled to range between 40 and 50 mm (CSIR 1997), with most rains falling in late summer (March-May). This was confirmed by an average of 47.5 mm measured over a 10-year period at the site (Turgis Consulting 2008). Rainfall is highly variable between years and often patchy. Rainfall seasons with over 100 mm are rare and were only recorded twice during the monitoring period (Figure 2). The prevailing wind is south-westerly, but strong, very dry easterly 'berg' winds occur during the autumn and winter months. Temperatures range between an average minimum of 8 ºC to an average maximum of 32 ºC (Mendelsohn *et al.* 2002). Rainfall in the observation period exceeded the expected annual mean three times – in 2009 with 154.6 mm, 2011 with 134 mm and in 2014,

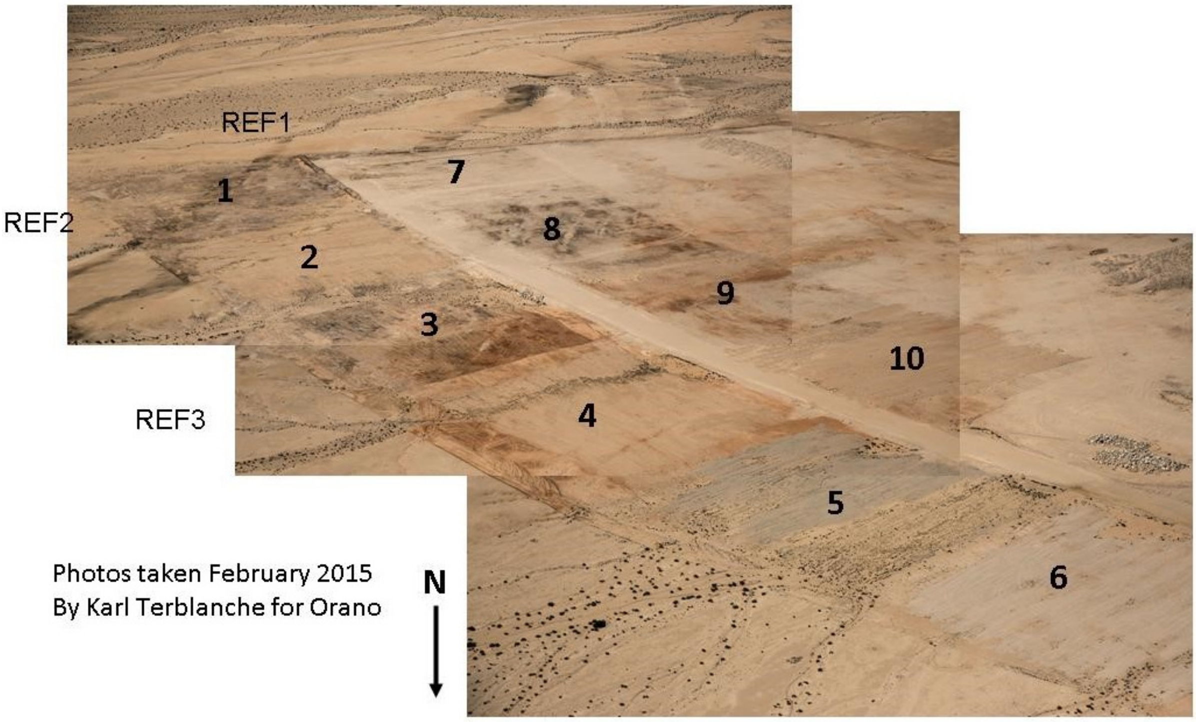

Figure 3: *Layout of rehabilitation site at Trekkopje Mine in 2015 (photo credit: Orano).*

when a total of 53.7 mm was measured. All other years were below average (Figure 2).

The mine is located on a gently west-sloping peneplain where runoff occurs as short-lived flows in response to rainfall in the catchment area. Evidence of runoff in the study area is in the form of shallow, sandy ephemeral drainage lines and sheet-wash surfaces. The streams terminate on the gravel plains west of the mine.

The uranium deposits lie close to the surface in calcium carbonate-cemented (calcrete) conglomerates of Tertiary age that fill palaeochannels incised into Precambrian/Cambrian meta-sedimentary rocks and intrusive granites. Trekkopje mine plans to use a strip-mining process that allows progressive rehabilitation as the ore body is excavated. The tailings from an alkaline leach process on an on-off heap leach pad will be backfilled into the open pit. Besides the backfilled areas, man-made landforms remaining after mining will include areas disturbed by infrastructure such as processing plants, offices and workshops, evaporation ponds, waste rock dumps and linear infrastructure such as roads, power lines and pipelines.

Post-mining land use is expected to be wildlife conservation and tourism as the mine is situated within a communal conservancy. The main question with regard to rehabilitation is whether these man-made landscapes can support the natural establishment of vegetation within a reasonable timeframe, for example one human generation. Restoration trials were set up with the main purpose of simulating the post-mining landscape and monitoring the re-establishment of natural vegetation.

Restoration trials

The test site covers 10 ha of a levelled former stockpile area and consists of ten 100 x 100 m plots with different surface treatments (Table 1). It was established in 2010 at the approximate geographic position: latitude 22º12'S, longitude 14º52'E (Figure 1). The eastern half of the area had been stripped of topsoil (Figure 3). The western part was covered with a layer of conglomerate as a base. The surface of this layer was compacted by the movement of heavy equipment. The rehabilitation trials were designed to answer the question whether vegetation would be able to re-colonise the disturbed areas without restoration measures or if interventions such as scarifying the compacted surface (Figure 4), replacing topsoil or applying some other fine-grained material like granite crusher dust or heap leach tailings would be required.

The first six 100 x 100 m plots in the eastern part were completed in December 2010 with six different treatments (Table 1), while the remaining four plots in the western part were completed in March 2011.

Figure 4: *The scarified surface of conglomerate still shows no plant growth after six years (photo: A. Burke).*

The southern half of this area was stripped of all conglomerate, while conglomerate was left on the northern half. The "controls" are disturbed areas which received no treatments. Three reference sites of comparable habitats, which provide the best approximation of the natural ecosystem before disturbance, were established in the vicinity. The sites were left to recover naturally, meaning that no irrigation, seeding or re-vegetating was undertaken. During an exceptionally good rainy season in 2011 runoff from shallow water courses to the east of the trials penetrated the trial area and flooded part of areas 4, 5 and 6. As these areas were rapidly colonised by plants, these flooded areas were considered an additional treatment and called "inflow" areas (Figure 5).

Field surveys

Soil was sampled after the rainy season (usually April-June) each year for six years during the period 2012-2017. Approximately 500 g of soil of the top 10 cm was collected within each trial and reference site. Three soil samples were taken randomly at each treatment and the reference sites. To be cost-effective, the three subsamples per treatment were then bulked for laboratory analysis.

Soil laboratory analysis

The soil samples were subjected to a standard farm soil analysis by Analytical Laboratory Services in Windhoek. This included pH (H_2O) (2:5), electric conductivity (ECw) (2:5), $CaCO_3$ (acid neutralisation, % $CaCO_3$ equivalent), organic carbon

Table 1: *Rehabilitation trial treatments at Trekkopje Mine ('Named' refers to the group of treatments under which the results of the soil samples were reported).*

Code	Treatment	Named
1	Area levelled to serve as a control	control
2	Application of a 10 cm thick layer of stored topsoil, 1 year old	topsoil
3	Scarifying (depth: ± 20 cm)	scarified
4	Scarifying and topsoil application (same topsoil as 2) plus inflow	topsoil
5	Application of granite crusher dust plus inflow	granite
6	Area covered in tailings plus inflow	tailings
7	Conglomerate removed to serve as control	control
8	Conglomerate removed and surface scarified	scarified
9	Conglomerate left and surface scarified	scarified
10	Conglomerate left and topsoil application (same topsoil as 2)	topsoil

Figure 5: *A good rainy season generated inflow into one of the restoration trials, resulting in an immediate response of the vegetation (photo: A. Burke).*

(Walkley-Black), organic carbon (calculated factor=1.724) and plant available P (Ohlsen *et al*. 1954). Extractable Na, K, Mg, Ca were measured using 1M ammonium acetate (pH 7.0) followed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). A particle size analysis used the pipette method (Analytical Laboratory Services 2012).

Data analysis

Soil properties that showed differences between treatments and reference sites and that are commonly used as indicators in soil studies were selected for further analysis. Means and standard deviations were calculated per treatment and per year and illustrated in graphs. Data were plotted and one outlier was removed (calcium content in one reference site in 2017 was measured 9 times higher than the highest previous record and was omitted).

Soil properties express themselves at a microhabitat level, although sampling is usually undertaken at a habitat level. For example on plains, considered a habitat in this study, there can be shallow furrows and depressions which are considered as microhabitats in this context. The variability of the data therefore has to be taken into account. In order to compare variability between different soil properties, the coefficient of variation was calculated by dividing the standard deviation of each treatment and soil property by its mean (Fowler & Cohen 1992).

RESULTS

Patterns of soil properties

Except for pH, clay content and organic carbon, soil properties showed a large range of values. For example electric conductivity ranged from 6.5 to 3,050 mS/m, calcium from 2,600 to 31,900 mg/kg, potassium from 32 to 308 mg/kg, magnesium from 22 to 458 mg/kg and phosphorous from 0.01 to 30 mg/kg. In all soil properties the highest value was at least ten times the minimum value.

Despite these considerable ranges, patterns were remarkably similar for five of the measured soil properties. Controls, topsoil-treated and scarified sites all showed higher electric conductivity, sodium, calcium, potassium and organic carbon content than the reference sites (Figures 6-8). Magnesium content was only higher in controls and scarified sites (Figure 8c). Calcium content in the inflow areas measured at an intermediate level (Figure 6c). Granite crusher dust and tailings-treated sites, inflow and reference sites showed the lowest values in electric conductivity, sodium, potassium and organic carbon content (Figures 6-8). Electric conductivity of tailings material is similar to the reference and inflow areas. Considering the soil properties individually, electric conductivity and sodium content are closely linked and show almost identical patterns (Figure 6a and 6b), indicating that sodium salts are likely the foremost contributor to the salinity of the various substrates overall.

***Table 2**: Coefficient of variation (standard deviation/mean) for soil properties at Trekkopje Mine for different treatments. (All values >1 indicate that the standard deviation is greater than the mean (bold); n=sample size for laboratory analysis, composed of three bulked field samples per year and treatment). The sample size for treatments differ because some treatments were duplicated and additional samples were taken in the field when required.*

	EC	Na	Ca	OC	pH	clay	K	P	Mg
Control (n=10)	0.63	0.73	0.29	0.93	0.04	0.37	0.59	0.77	0.59
Topsoil (n=17)	0.55	0.73	0.35	0.35	0.04	0.39	0.36	**1.06**	0.48
Scarified (n=14)	0.49	0.58	0.40	0.68	0.02	0.38	0.33	0.54	0.41
Granite (n=6)	0.23	**1.16**	0.42	0.83	0.02	0.36	0.18	0.43	0.48
Tailings (n=6)	0.46	0.87	0.91	**1.10**	0.09	0.55	0.33	0.89	0.24
Inflow (n=16)	0.71	**1.76**	0.74	0.96	0.03	0.43	0.48	**1.25**	0.47
Reference (n=17)	**1.58**	**1.75**	0.33	0.67	0.05	0.74	0.90	**1.20**	0.67

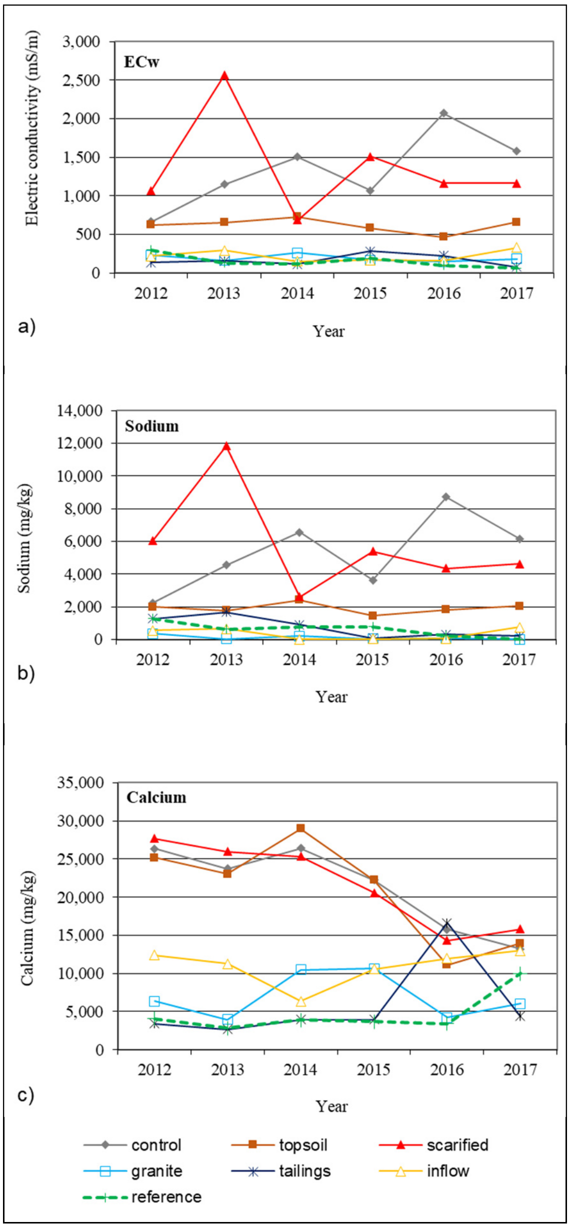

***Figure 4**: Mean of soil properties at Trekkopje Mine in the central Namib Desert on rehabilitated surfaces: a) electric conductivity, b) sodium content and c) calcium content (n=1-3 for treatments and 9 for reference from 3 bulked subsamples per treatment and year).*

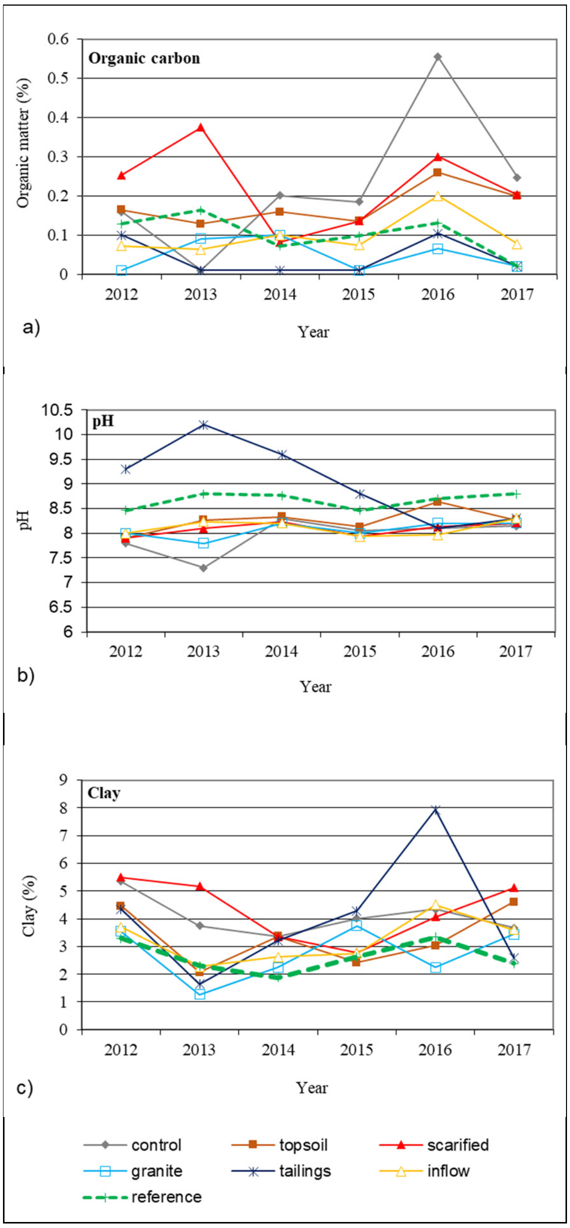

***Figure 5**: Mean of soil properties at Trekkopje Mine in the central Namib Desert on rehabilitated surfaces: a) organic carbon content, b) pH and c) clay content (n=1-3 for treatments and 9 for reference from 3 bulked subsamples per treatment and year).*

Variability of soil properties

The greatest variability (i.e. coefficient of variation) was shown in electric conductivity, sodium content and phosphorus content, while pH showed the lowest variability overall, followed by potassium, clay and magnesium content (Table 2). Soil properties that remained comparatively stable in the reference sites over the years overall were calcium content (Figure 6c), organic carbon (Figure 7a), pH (Figure 7b), clay content (Figure 7c), potassium (Figure 8a) and magnesium content (Figure 8c).

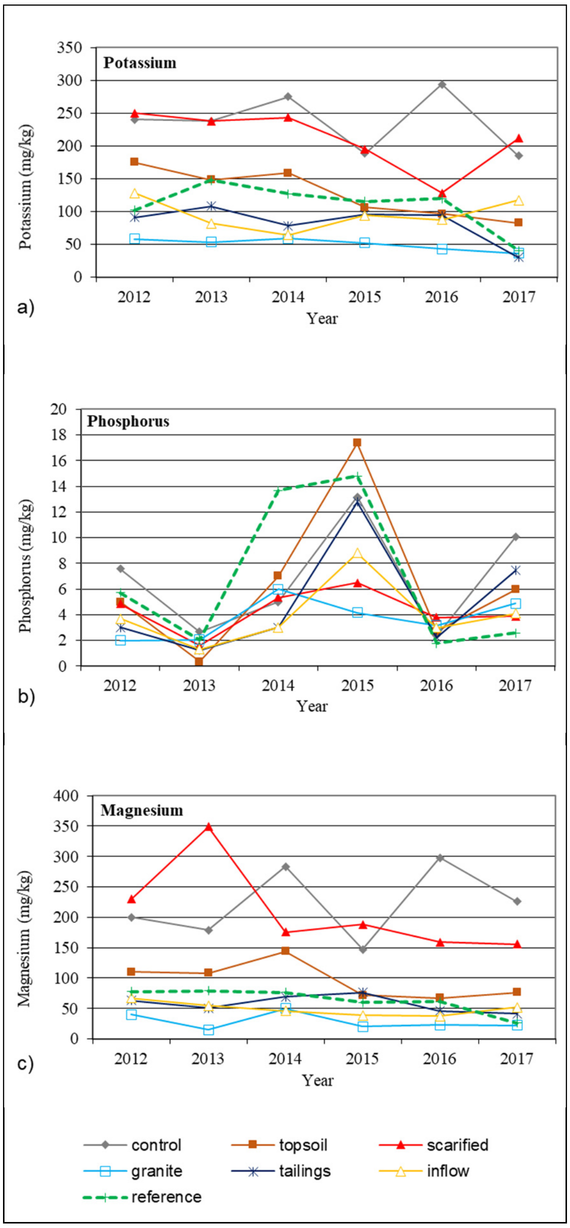

***Figure 6**: Mean of soil properties at Trekkopje Mine in the central Namib Desert on rehabilitated surfaces: a) potassium, b) phosphorus and c) magnesium content (n=1-3 for treatments and 9 for reference from 3 bulked subsamples per treatment and year).*

Trends over time

On rehabilitated sites, trends of declining calcium content were found for the control, topsoil-treated and scarified sites (Figure 6c). The pH declined on the tailings-treated site (Figure 7b) from very high values due to residual alkaline leach reagents (sodium carbonate and bicarbonate) being flushed out. Declining potassium concentrations were observed on the topsoil and granite crusher dust treated sites (Figure 8a).

Effect of rainfall

None of the soil properties showed a direct correlation with rainfall, although phosphorus content increased steeply on the reference sites in 2014 and remained high in 2015, which could be linked to the rains in 2011 and 2014 (Figure 1). However, it also increased in all other treatments, with a particularly steep increase in control, topsoil and tailings-treated sites (Figure 8b) and a slight increase was indicated in 2017 in all sites without significant rains. A direct link to rainfall is therefore unlikely.

DISCUSSION

Soil properties are meant to be indicators of ecosystem processes in restoration monitoring. If restoration is successful they are expected to show a trend towards a biochemically stable situation, closely resembling the parameters in comparable natural habitat. While this has been demonstrated in restoration projects in mesic (Campbell 2002) and semi-arid (Alday *et al.* 2011) environments, little information is available for arid environments. This is partly because ecological processes are extremely slow, and most studies are not sufficiently long-term to show these trends. But it may also mean that arid ecosystems, that follow pulsed processes (Noy-Meir 1973), do not naturally show stable conditions in soil properties. However, restoration monitoring is expected to include “process” indicators and soil properties have been advocated in most restoration guidelines (e.g. Tongway & Hindley 2004; SER 2005; McDonald *et al.* 2016). Six years of monitoring soil properties at Trekkopje Mine in the central Namib Desert provided some insights regarding trends in soil properties in an arid environment in less than a decade and is presented here as a case study.

Variability of data

The variability of soil properties in the natural environment needs to be addressed to select appropriate properties against which the rehabilitated sites can be measured. Variability may be a result of (1) inherently fluctuating conditions in an arid ecosystem (Francis *et al.* 2007) or (2) related to micro-topography, which could cause differences even within one treatment, for example between mounds and furrows (Banning *et al*. 2008) and (3) the fact that arid ecosystems have likely the greatest spatial variation in soil properties of any ecosystem (Crawford & Gosz 1982). This is due to patchy rainfall, uneven vegetation cover which can create 'fertile islands' (Schlesinger *et al*. 1996) and micro-topography.

To overcome this inherent variability, sufficient soil subsamples have to be collected for bulking before laboratory analysis. However, there is considerable debate around the appropriate size of subsamples for bulking, ranging from two (University of Cornell 2015) or four subsamples (Environment Protection Authority 2005) to 40 in agricultural studies (Adetunji 1994). Practical considerations such as available budget, time and logistics influence the opted for sample size and three discrete subsamples were therefore selected in this study. The number of subsamples for bulking was perhaps insufficient to account for the spatial variability within each treatment site. Nevertheless, the reference sites in this study showed reasonable stability in the properties calcium content, organic carbon, pH, clay content, potassium and magnesium content which showed relatively low variability in the data (Table 2) and remained comparatively constant over the years (Figures 6-8). These soil properties were not even affected by rainfall patterns over the monitoring period, indicating that the number of subsamples for bulking may have been sufficient in this instance.

Differences between treatments

In contrast to this relative stability in some soil properties at the reference sites, all investigated soil properties, except for clay content, showed differences between the various restoration treatments. The controls, topsoil-treated and scarified sites had higher electric conductivity, calcium, potassium and organic carbon concentrations than the reference sites. Calcium and potassium may have been made available by the mechanical action of scarifying and the handling of topsoil with machinery which breaks up the soil structure.

The higher values of electric conductivity and calcium in the topsoil-treated sites are surprising, as they should be similar to the reference sites. However, stripping of topsoil was not always done according to specifications and saline and alkaline subsoil material may have been mixed in with the topsoil.

Therefore control, scarified and to some extent topsoil-treated sites present samples of subsoil. This subsoil is derived from conglomerate of ancient paleochannels which are highly variable and consist of mainly conglomerate with lenses of sand, clay and silt (Orano, internal geological report). The conglomerate is made up of debris of dolerite, gneiss, granite, marbles, pegmatite and quartz. It is cemented largely by calcite, and to a lesser extent by dolomite and the sulphates celestine and barite. The upper conglomerate unit has been cemented by gypsum. Gypsum or a thin cover of alluvium overlay the conglomerate (Orano, internal geological report). Calcium is therefore a major chemical element in the subsoil which explains the high calcium values found in the control, scarified and topsoil-treated soil samples (Figure 6c). Also, higher electric conductivity could be expected in subsoil, which was confirmed when the subsoil EC was measured at various sites on the mine (S. Müller, pers. obs.).

The higher organic carbon content in the soil of rehabilitated sites is more difficult to explain, because it is delinked from patterns in standing biomass (vegetation). The most vegetated sites are those which received water inflow and they rank low in soil organic carbon content (Figure 7a). In these areas vegetation cover was even higher than for the reference sites in some years (A. Burke, pers. obs.), but this is clearly not reflected in organic carbon content of the soil. There could be three reasons for this: (1) The breakdown of the vegetation and incorporation of organic matter in the soil takes longer than five years in this environment. The highest vegetation growth was observed in 2012 after the 2011 rainy season and litter from this exceptional growth should be detected in the soil by now, if it was broken down immediately *in situ*. (2) Organic carbon content in the soil may not be determined by the standing vegetation, but by wind-blown detritus collecting in suitable micro-catchments on the soil surface in this arid environment. Windblown detritus was observed in the rehabilitated areas and this would also explain why the least vegetated sites – hardly any vegetation growth has been observed in controls and scarified sites, and very little in the topsoil-covered areas – showed the highest organic carbon content (Figure 7a). (3) Organic carbon concentrations only reached a maximum of 1 % and this generated such low values that the results would be spurious. Yet these low values in organic carbon correspond with other records from the central Namib, where 0.2-0.8 % organic carbon content was measured in topsoil along a transect from the coast to the base of the escarpment (Scholz 1963), and only 0.03 % organic matter was measured in a calcareous soil on the gravel plains near the research station Gobabeb (Scholz 1972) and 0.2 % in a gypsisol at the coast (Petersen *et al*. 2010). Elsewhere, arid medium-textured and fine-textured soils in India were also reported with a very low organic carbon content (0.05-0.4 %) (Praveen-Kumar *et al*. 2009). These low values are therefore expected in an arid environment. Clay content influences organic carbon (Praveen-

Kumar *et al*. 2009; Petersen *et al*. 2010), but since there were no major differences between the treatments this could not explain the distribution of organic carbon.

Soil properties at other arid sites

The clay fraction of central Namib plain soil samples ranged 1.8-5.3 %, and was 0.5 % at Gobabeb (Scholz 1963, 1972), which is within the range of the values measured at Trekkopje. Measurements of soil pH in the coastal central Namib (gypsisol) indicated a mean of 8.3 and mean electric conductivity of 200 mS/m (Petersen *et al*. 2010), which corresponds well with the measurements at the Trekkopje reference sites. At a mine site near the escarpment a pH of 8.1-8.75, organic carbon of 0.07-0.17 % and clay <6 % were measured in colluvial soils. Plant available phosphorus was reported at below 10 mg/kg in arid soils in India (Praveen-Kumar *et al*. 2009). The measured values of these soil properties at Trekkopje are therefore not unusual.

Trends over time

If rehabilitation has been successful, then a trend in indicators is expected towards the values measured at reference sites. In this study only two consistent trends were shown in variables which were also relatively stable at the reference sites: declining calcium content on the control, topsoil-covered and scarified sites (Figure 6c), and declining pH on the tailings.

Regarding the trend in pH, the tailings were treated with sodium bicarbonate and sodium carbonate during the leaching process resulting in a very high pH which is slowly declining to approach the pH of the reference sites. The uranium ore was then washed with fresh water before the start of alkaline heap leaching to remove salts such as sodium chloride, sodium sulphate and some of the calcium sulphate. Diverting from these trends is pH which was higher at tailings-treated and reference sites. This trend is therefore not natural, but man-made.

The declining trend in calcium on control, scarified and topsoil-treated sites could be due to the fact that large amounts of calcium were now exposed from the subsoil and gradually leached from the soil. Interestingly no such trend was shown in salinity at these sites, which according to the expected soil development processes should also be showing a decline over the years. However, this trend may be masked by the high variability in the soil and only evident in calcium because calcium content was initially extremely high.

Effect of rainfall

Only phosphorus content indicated a link to rainfall pattern with a large spike in phosphorus after the 2014 rains in the reference sites, but also evident at all other sites (Figure 8b). Phosphorus is believed to be in low supply in arid region soils (Praveen *et al*. 2009), which was supported by this study. It is also affected by carbonate, alkaline and calcic soils which bind phosphorus in insoluble form (Lajtha & Schlesinger 1988). Both the low content overall, and the effect of these alkaline soils may influence the results and not show consistent patterns or trends. The influence of rainfall needs to be seen in the light of these other variables. Soil processes in arid environments are not only driven by water availability, but the effect of light (photodegradation) and spatial heterogeneity also need to be taken into account (Austin 2011). Subsurface processes often have unique controls which are not directly linked to positive precipitation/primary production relationships (Austin 2011). In fact, decomposition in deserts is not necessarily correlated with annual precipitation, as demonstrated by a 10-year study in North America (Vanderbilt *et al*. 2008).

Carbonates accumulate during and after rains at the depth of water penetration in the soil (Crawford & Gosz 1982). As rainfall is extremely patchy in deserts this can result in a very uneven distribution of carbonate layers in the soil (Mac Mahon 1981). This relates to the contemporary carbonate distribution as much is represented by remnants of calcrete layers in the soil profile that were laid down in the past during more humid conditions. Another factor contributing to spatial heterogeneity of desert soils is the intensity of rainfall. Rains often fall in storm events which results in sheet wash and overflowing washes and rivers, depositing alluvial debris (Crawford & Gosz 1982).

The spike in available phosphorous at all sites in 2014 and 2015 could be related to a slow release of phosphorous following the 2011 rains, followed by a further stimulus of rain in 2014. Decomposition rates in deserts are very low (Fernandez *et al*. 2004) and it would therefore not be surprising if it takes three to four years until organic matter is broken down into available nutrients. The lack of a direct link between organic matter and soil organic carbon content may further support this hypothesis.

Towards soil indicators

In view of mostly inconclusive results, it is difficult to single out soil properties that may make useful indicators in this environmental setting in the short term. Calcium content is the only variable which, with some extrapolation, indicates an overall decline in the rehabilitated sites and thereby some form of soil development. In the natural course of events this is expected because the removal of calcium is the next step in soil development, once soluble salts have been removed. So far calcium content therefore provides the only usable indicator in the short term.

Soil organic content has always been advocated as a key indicator for soil fertility (Ruiz-Jean & Aide 2005), but the results of this study call this practice into question in arid areas. Organic matter content may not be an appropriate soil fertility indicator here, either because of the long lag period in the breakdown of organic matter or because this indicator is not directly affected by standing biomass and therefore does not necessarily guarantee that soils with high organic matter content are also best suited to support vegetation development.

Ultimately critical benchmarks in soil properties which facilitate plant establishment need to be established. Half of the rehabilitated sites (control, scarified and topsoil-treated) are presently sodic, saline and alkaline and therefore from a biochemical perspective unlikely to support the establishment of a lasting plant cover. Soil treatments may therefore be required to reduce salinity and sodicity. On the other hand, many desert plants are adapted to cope with high salinity (Evenari *et al*. 1982) and this may be less of a problem than anticipated. Surprisingly, annual grass established well after a reasonable rain event on another rehabilitated site on Trekkopje Mine with similarly "unsuitable" soil conditions (measured, but not presented here). This could be explained by the leaching of salts and loosening of the crust of the surface layers which was adequate to make the substrate suitable for the germination of grass. Whether this was a once-off event or the initiation of more permanent plant cover needs to be monitored.

Soil-plant relationships are poorly understood on a species-level for plant species in the study area and salinity tolerance levels are unknown. A study along a north-south transect through Namibia's semi-arid savanna and desert regions demonstrated well that plant species richness is likely influenced by salinity, clay content and pH (Medinski *et al*. 2010). Electric conductivity of 100 mS/m for example was cited as a threshold for supporting reasonable species richness (Medinski *et al*. 2010). Although salt tolerance levels of many cultivated plants have been established (e.g. Abbas *et al*. 2015; Demiral 2017; Kalantari *et al*. 2018), only some desert plants have been investigated. *Suaeda vera* can tolerate up to 1930 mS/m (Herrero & Castaneda 2013) and *Salsola soda* up to 1000 mS/m (Centofani & Banuelos 2015), which means most of the rehabilitated sites would be suitable for these two highly salt-tolerant species, if salinity was the only limiting factor. However, these two species are adapted to very high salinity and therefore exceptions – most Namib perennials likely require lower salinity levels to maintain healthy populations.

Implications for restoration monitoring

The monitoring of soil properties of rehabilitated sites at a mine in the central Namib illustrates the challenges restoration practitioners face when working in arid environments, which are similar to rehabilitated sites in other parts of the world (Lamp *et al*. 2015). Six years of monitoring soil properties generated inconclusive results. The question which treatments would provide the most effective restoration method could therefore not be answered. This means that much longer monitoring timeframes are needed, perhaps other indicators need to be included and the sampling intensified. Alternatively, the conventional approach to selecting monitoring parameters for restoration needs to be revisited in arid areas in favour of different methods altogether to demonstrate an "ecologically functioning" ecosystem. Researchers have suggested "state-and-transition" models (Westoby *et al*. 1989; Hobbs *et al*. 2014) as a more appropriate benchmark in arid ecosystems. However, this requires that the variables driving individual "states" and potential thresholds for tipping points in particular environmental settings are well understood at a habitat level.

This is not the case in the central Namib and collecting more information on ecological processes is therefore required in the meantime. Despite the fact that, apart from calcium content, no other soil properties showed clear trends, a standard farm analysis of the soil should be continued as part of the monitoring programme. However, the number of subsamples for bulking should be increased and tested whether this reduces in-site variability of soil properties. (1) Trends may emerge in other properties after a longer time and (2) these properties are required to calculate other indices of soil fertility and characterisation. If costs are a limitation, monitoring frequencies could be reduced to two- or even three-year intervals. Exceptional rainfall seasons, however, should always be monitored as this is when changes are likely to be detected.

Although this study by sampling is a case study and limited to descriptive statistics, several case studies investigating the same questions and showing similar results may eventually allow the drawing of generalised conclusions (Tavares *et al*. 2016). Presentation of these monitoring data also provides information to other researchers in this field and assists in designing appropriate monitoring protocols. Most restoration projects do not plan for long timeframes (Ngugi & Neldner 2015), but this study indicates that it is compulsory in an arid setting and long-term data collection which consistently applies the same methodology is essential.

CONCLUSIONS

Rehabilitated sites in the arid Namib Desert showed no clear trends in soil properties over a six-year monitoring period, except in calcium content at subsoil-dominated sites. Soil organic carbon content was not correlated with standing biomass and it is therefore questionable whether it provides a suitable indicator for soil fertility in arid regions in a restoration context.

Long term, site-specific monitoring is needed in arid regions to illustrate recovery of disturbed sites by means of process indicators. However, whether benchmarks derived from comparable natural environments can ever be reached within the timeframe usually applied to restoration projects is questionable.

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