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Determining rehabilitation effectiveness at the Otjikoto Gold Mine, Otjozondjupa Region, Namibia, using high-resolution NIR aerial imagery

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ABSTRACT

Mine rehabilitation is compulsory under the Namibian Environmental Management Act. B2Gold's Otjikoto gold mine complies by committing to rehabilitation of their waste-rock dumps and other disturbance features within their mining licence area in the Otjozondjupa Region. As the mine is in the early stages of operation and has committed to run-of-mine rehabilitation, there have been some rehabilitation attempts. Initial rehabilitation of an abandoned section of a district gravel road (D2808) and the western face of a waste rock dump (known as SP11) has been undertaken. Rehabilitation measures included ripping of the soil surface of the gravel road as well as covering the ripped soil surface and the waste rock dump slopes with stored topsoil removed from the first mining cut before it was excavated. We investigated the extent of vegetation establishment of these rehabilitation measures with the aid of high-resolution near infra-red aerial imagery coupled with ground-based observations on established plant biomass. It was evident that simple ripping of the road surface allowed limited establishment of grasses, which was greatly improved if the ripped surface was covered by stockpiled topsoil. Likewise, covering the waste rock dump with topsoil resulted in the natural establishment of various grasses, but also the leguminous shrubs *Dichrostachys cinerea* and *Mundulea sericea*. Erosion of the applied topsoil on the waste rock slope was, however, found to limit vegetation establishment. The natural establishment of both *Dichrostachys cinerea* and *Mundulea sericea* indicates a high potential for these species to be used for basic stabilisation of the slopes, possibly enabling colonisation by a variety of other species which we have listed. Several techniques published to aid the stabilisation of the slopes and establishment of vegetation cover were also reviewed and contextualised for Namibian conditions.

Keywords: *Dichrostachys cinerea*; gravel road rehabilitation; *Mundulea sericea*; natural revegetation; NDVI; waste rock dump rehabilitation

INTRODUCTION

Open-cast mining is known to have a destructive effect on the environment. Next to the physical destruction of habitats for mining and associated infrastructure, add-on effects like wind and rain erosion, dust generation, seepage of toxic wastes (including heavy metal pollution) and ground water contamination are common problems (Hahn et al. 2004, Navarro et al. 2008, Sheoran et al. 2010, Mapaure et al. 2011, Kossoff et al. 2014). Under the Mine Closure Framework, members of the Namibia Chamber of Mines subscribe to timely establishment and implementation of a closure plan for any particular mine. From an environmental perspective, this Mine Closure Framework prescribes to "protect public health and safety and the environment by using safe and responsible closure practices; reduce or eliminate adverse environmental effects once the mine ceases operations; establish conditions that are consistent with the predetermined end-use objectives and reduce the need for long-term monitoring and maintenance by establishing effective physical,

chemical and ecological stability of disturbed areas" (Chamber of Mines of Namibia 2010). Legally, the reduction of mining impacts on the environment in Namibia is required for a licence to operate under the Environmental Management Act 7 of 2007 (Government of the Republic of Namibia 2007) and the Minerals (Mining and Prospecting) Act 33 of 1992 (Government of the Republic of Namibia 1992). Implicitly, this includes effective mine restoration or rehabilitation.

Effective mine-site restoration requires an understanding of the purpose of land use after mine closure, functioning of the landscape, and consequently an agreed set of targets between different stakeholders of what needs to be achieved post-mining (Chamber of Mines of Namibia 2010, Tongway & Ludwig 2012). Restoration is defined as "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability" (Society for Ecological Restoration Science & Policy Working Group 2002). Depending on the severity of degradation, the resilience of the ecosystem and the set restoration

targets, different categories of restoration are recognised: (i) near-natural restoration; (ii) ecological restoration; (iii) ecological rehabilitation and (iv) reclamation. Whereas restoration aims at returning the ecosystem to a pre-disturbance state, rehabilitation aims at improving ecosystem functionality without necessarily returning to the pre-disturbance state (van Andel & Aronson 2012). Reclamation is often achieved by merely doing basic physical shaping to reduce visual concerns. Given the nature and severity of open-cast mining operations, a mine closure plan would mostly not be able to achieve much more than basic reclamation, although at a more local scale some parts of a mining footprint should achieve rehabilitation or ecological restoration if effectively managed.

To fulfil their statutory obligation and implement best practice rehabilitation the Otjikoto Gold Mine initiated experimental rehabilitation efforts on its SP11 waste rock dump, as well as an abandoned section of the district gravel road (number D2808) in the mining area within two years of commencing mining operations. Best practice dictates that reclamation and restoration activities do not only commence post-mining but integrate into run-of-

mine activities (Cooke & Johnson 2002). The targets of this reclamation were to prevent dust generation from the surface, as well as preventing water erosion of the waste rock dump slopes.

The aim of this study was to assess the effectiveness of vegetation establishment (considering spatial homogeneity) on the SP11 waste rock dump and the abandoned D2808 road section using high resolution Unmanned Aerial Vehicle (UAV) visual and near infra-red (NIR) imagery, ground-truthed with on-site physical surveys.

METHODS

Study Site

The Otjikoto Gold Mine is situated in the Otjozondjupa Region of Namibia along the B6 road north of Otjiwarongo towards Otavi (Figure 1). The natural vegetation belongs to the Thornbush Savanna *sensu* Giess (1998). The vegetation can best be described as densely encroached, closed tall bushland *sensu* Edwards (1983) (own observation). The tree and shrub layers are dominated by various *Acacia* (*sensu lato*) species, specifically *A. mellifera* subsp. *detinens* and *A. luederitzii*. *Dichrostachys cinerea*

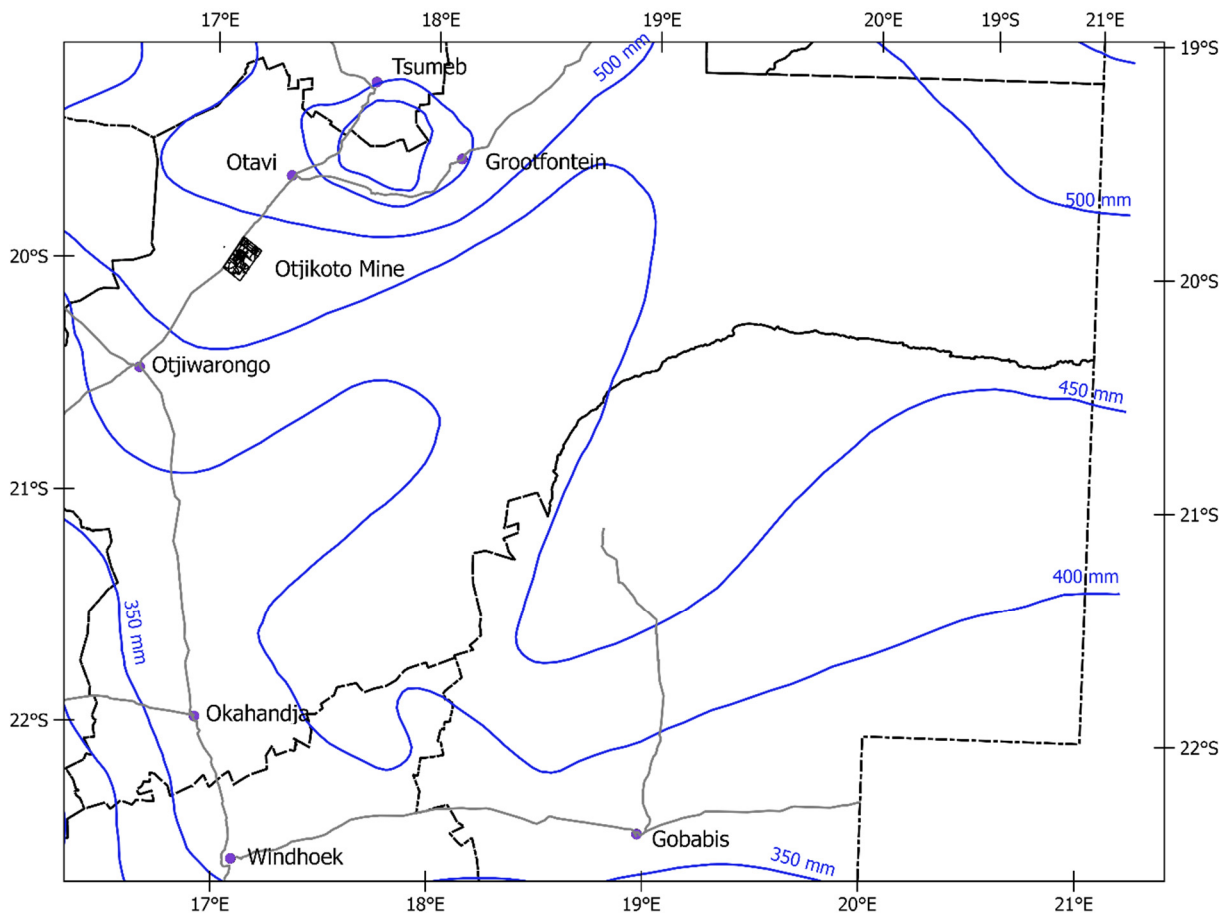


Figure 1: General position of the Otjikoto Mine in the Otjozondjupa region, central Namibia. The average annual rainfall is indicated in blue. Data source: NARIS (2001).

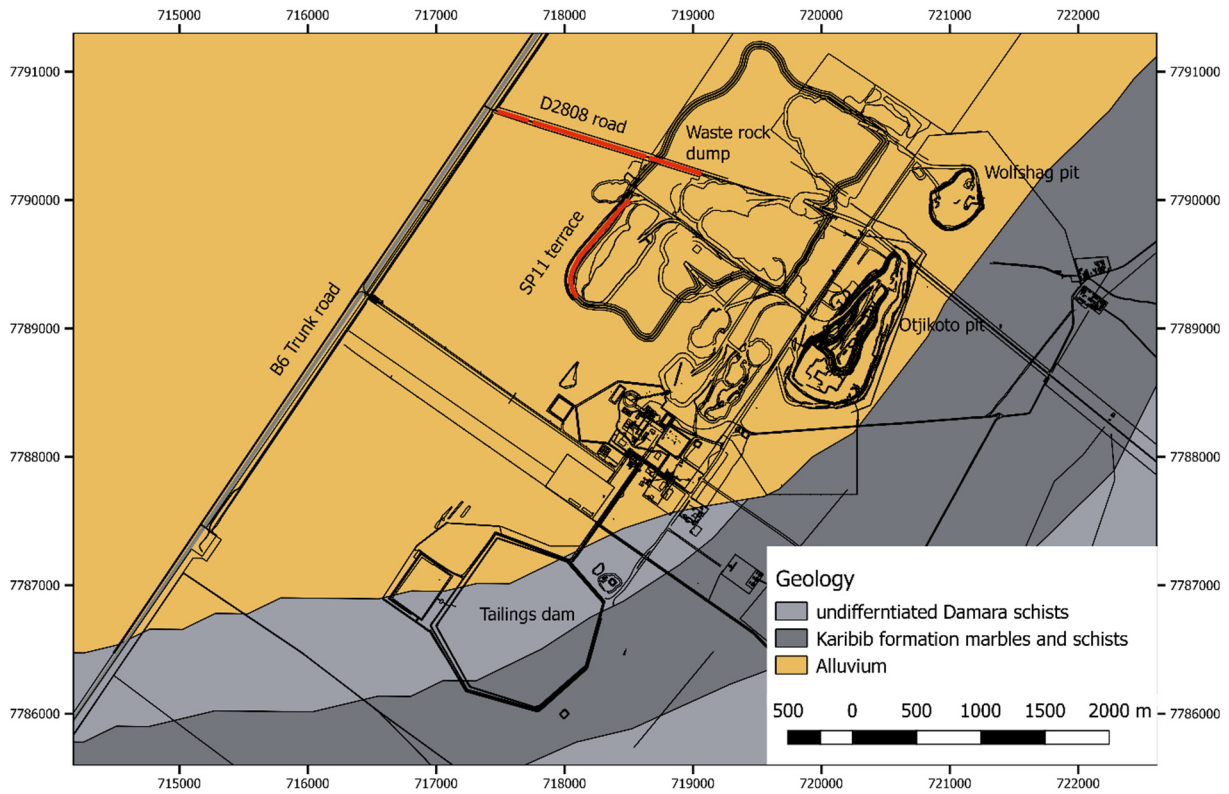


Figure 2: Overview of the Otjikoto Mine, indicating the basic surface geology. The study areas for this paper are indicated in red. Geological data source: Geological Survey (1980).

and *Catophractes alexandri* are also common. With occasional *Terminalia prunioides* trees, this vegetation forms a transition to the Karstveld *sensu* Giess (1998) further north.

The open-cast mine pit (Otjikoto Pit) is situated on rocks of the Karibib formation, with mostly marbles, schist and ortho-amphibolite (Geological Survey 1980). The study site (SP11 waste rock dump and abandoned section of the D2808 gravel road) is on an alluvial plain to the west of the pit, dominated by mollic leptosols (i.e. shallow, stony, dark, fine-grained soils over a petro-calcic horizon) as dominant soil type (ICC et al. 2000) (Figure 2). The climate is semi-arid with summer rainfall, with a mean annual precipitation of between 450 and 500 mm. Rainfall is generally between December and April each year (Mendelsohn et al. 2002).

Abandoned road and waste rock rehabilitation sites

A section of the original district road (number D2808) was relocated northwards in 2013 as its route crossed the mining area (Figure 2). The road was originally constructed with readily available calcrete gravel, which was compacted. The unaffected section of the road within the mining area, not impacted by excavation, was partially reclaimed in December 2016 under the mine environmental management programme (Figure 3). The entire road surface was

ripped with a bulldozer, and stored topsoil was used to cover the ripped road surface (ca 8 to 9 m wide), but not the adjacent road reserve. Topsoil covering varied amongst the different sections as detailed in Table 1.

The SP11 waste rock dump (Figures 2 and 6) was formed from the ore-bearing marble crush and overburden material extracted from the initial Otjikoto pit. The dump was terraced, with 20 m high terraces sloped at 18°, interspersed with 5 m horizontal benches. The lower terraced slope, once completed, was horizontally ripped and covered with a 15 cm layer of soil removed from the Otjikoto pit before mining in 2013. Section WRD2015 was covered in December 2015 and Section WRD2016 in December 2016 and January 2017 (Figure 6).

The Wolfshag and Otjikoto topsoils differ in that Wolfshag topsoil is a deeper soil (up to 70 cm deep) with less calcrete than the soils from Otjikoto. Both the Wolfshag and Otjikoto topsoils are sandy loams (19% clay content, 62% and 69% sand content for Otjikoto and Wolfshag respectively). The soils both have a fairly high pH of 8.4 to 8.5 and an electric conductivity of 166 µS/m and 142 µS/m for Otjikoto and Wolfshag respectively (Diener 2018).

Table 1: Segments identified along the abandoned part of the D2808 gravel road, with their treatment. Positions are given as UTM Zone 33S co-ordinates.

| | Western extent | Eastern extent | Length (m) | Treatment |
|-----------|---------------------|---------------------|------------|--|
| Section 1 | 717488.3, 7790687.7 | 717739.0, 7790611.1 | 262.1 | Ripped road surface, covered unevenly to 15 cm depth with topsoil from Wolfshag Pit area using a bulldozer to spread |
| Control | 717739.0, 7790611.1 | 717944.8, 7790548.1 | 215.2 | Ripped road surface, no topsoil cover |
| Section 2 | 717944.6, 7790548.1 | 718345.8, 7790425.4 | 419.5 | Ripped road surface, covered with topsoil from Wolfshag Pit area to more than 30 cm depth, graded |
| Section 3 | 718345.8, 7790425.4 | 718660.8, 7790329.5 | 329.3 | Ripped road surface, covered with topsoil from Wolfshag Pit area to approximately 15 cm depth, graded |
| Section 4 | 718670.8, 7790326.2 | 719137.2, 7790183.4 | 487.8 | Ripped road surface, covered with topsoil from Wolfshag Pit area to approximately 15 cm depth, graded |

Drone survey

An aerial survey of the D2808 and the waste rock dump was undertaken on 22 March 2017. For the purpose, four flights with an eBee (Sensefly) were undertaken. Each site was flown twice, once with a Canon G9X Red-Green-Blue (RGB) camera, the second flight with a Canon S110 camera modified for Near Infra-Red (NIR) photography. The G9X camera records regular colour photos (RGB) at 450 nm (blue), 520 nm (green) and 660 nm (red). The S110 camera has been modified to record at 550 nm (green), 625 nm (red) and 850 nm (NIR) (senseFly 2014, 2016). The weather was partially cloudy, with an easterly wind between 3 and 6 m/s. The aerial photos were stitched into an orthophotograph with Pix4D software (*Pix4Dmapper Pro* 2016), without using any ground control points. Georeferencing thus relied solely on GPS locations tagged to the individual images by the drone autopilot. Flight and image characteristics are detailed in Table 2.

Aerial image analysis and data extraction

During stitching the individual images to an orthophoto with Pix4D, a digital surface model (DSM) is created. The RGB orthophoto was only

used for visual interpretation and not processed further. From the NIR image colour indices for the three bands (red, green and NIR) were calculated, and from these the two vegetation indices NDVI (Tucker 1979, Bannari et al. 1995) and Modified SAVI (Qi et al. 1994a) were created. The original Soil Adjusted Vegetation Index (SAVI) (Huete 1988) was developed to compensate for differing background soil brightness, especially in situations with low vegetation cover. However, this index depends on a (known) soil brightness factor *L*, and on the degree of vegetation cover. With this dependability in mind, Qi et al. (1994) developed a way in which the *L* factor could be calculated from the NIR and red reflectance, thus negating the need to independently determine the value of *L*. This Modified SAVI (or MSAVI2) is relatively insensitive to soil brightness, and thus more effective than the NDVI in situations of low vegetation cover, i.e. with a Leaf Area Index (LAI) of below 1.2 (Qi et al. 1994b). For comparison, an LAI of 1.2 corresponds to between 48% canopy cover in maize fields and 58% canopy cover in wheat fields (Nielsen et al. 2012).

The RGB images were used as a baseline map in QGIS (*QGIS 2.14.5-Essen* 2016). As the Pix4D

Table 2: Flight and photograph characteristics during the aerial survey of an abandoned section of the D2808 road as well as the waste rock dump at Otjikoto Mine.

| | Flight 1 | Flight 2 | Flight 3 | Flight 4 |
|--|---|---|---|---|
| Target | D2808 | D2808 | Waste Rock Dump | Waste Rock Dump |
| Camera | S110 (NIR) | G9X (RGB) | G9X (RGB) | S110 (NIR) |
| Start of flight | 15h22 | 16h05 | 16h32 | 16h59 |
| Flight duration | 19 min 20 sec | 18 min 34 sec | 19 min 50 sec | 22 min 44 sec |
| Planned ground sampling distance | 5 cm | 5 cm | 5 cm | 5 cm |
| Average altitude | 143 m | 211 m | 211 m | 143 m |
| Planned individual image footprint | 200.0 x 150.0 m | 273.6 x 182.4 m | 273.6 x 182.4 m | 200.0 x 150.0 m |
| Planned lateral / longitudinal overlap of images | 60% / 75% | 60% / 75% | 60% / 75% | 60% / 75% |
| No of photos taken | 222 | 191 | 167 | 221 |
| Sun azimuth (A_z) (Hoffmann 2015) | 296.4° | 288.9° | 285.2° | 282.0° |
| Sun elevation (β) (Hoffmann 2015) | 49.2° | 39.8° | 33.8° | 27.6° |
| Shadow length per 1 m height (Hoffmann 2015) | 0.86 m | 1.20 m | 1.50 m | 1.91 m |
| Area covered | 128.137 ha | 178.731 ha | 128.172 ha | 105.587 ha |
| Resulting image quality: Average ground resolution | 5.08 cm | 4.7 cm | 4.61 cm | 4.82 cm |
| Resulting image quality: RSM error | X: 0.6223 m Y: 0.4636 m Z: 1.5477 m | X: 0.6063 m Y: 0.2747 m Z: 1.0491 m | X: 0.3637 m Y: 0.3456 m Z: 0.4828 m | X: 0.4510 m Y: 0.5628 m Z: 0.3798 m |

software georeferenced these images in the UTM Zone 33S projection (based on WGS84), this was taken as the projection for the entire project. From this, the centre of the D2808 road was marked with a line on the RGB image. For each of the five visually identified road sections (Table 1), a digital transect line was constructed, just shorter (ca 1 m) than the full extent of the road section length, to avoid edge effects. This section centre-line was used with the QGIS plugin "swath profile" to extract a series of swath profiles parallel to the centre-line, following the method described by Hergarten et al. (2014). Each swath was 0.2 m from the previous. The NDVI values and MSAVI2 values were sampled every 0.2 m along the entire swath. These values were averaged along the swath. In this way, a profile of the average NDVI values as well as average MSAVI2 values (both with standard deviation) up to 27 m either side of the centre line was established for each road section. This profile can roughly be subdivided into the following zones from the centre: 0 - 4.5 m: road surface, 4.5 - 13.5 m: road verge (road reserve), and 13.5 - 27 m: natural vegetation. This applies to both sides of the centre-line.

For the terraced SP11 waste rock dump, a similar method was followed. For ease of interpretation, a set of contour lines, with 1 m altitudinal difference, was generated from the DSM of the RGB image. The 1525 m contour line was taken as the top edge of the slope which was reclaimed by covering it with topsoil. Again, two sections could be identified (Table 3), being reclaimed in two different years. Two lines were constructed following the 1525 m contour, representing the top edge of these two sections. Again, using the plugin "swath profile", the average NDVI and average MSAVI2 values were extracted along a series of swath lines 0.2 m apart, sampling each 0.2 m along the swath. Swaths were extracted up to 35 m from the base line. For orientation purposes, an altitudinal profile was also extracted from the RGB DSM. As the "swath profile" plugin extracts data on either side of the base line, the profile extends to the top of the dump. The northern part, next to the WRD2016 section, has been freshly deposited / levelled and thus has no vegetation establishment. This part thus serves as control. The

southern part of the top of the dump, adjacent to the WRD2015 section, has been fairly undisturbed for at least two seasons and shows some natural vegetation establishment. This section can therefore be regarded as a further treatment of rehabilitation without intervention.

Biomass

As ground-truth to the aerial images, biomass clippings were conducted on the rehabilitated section of the D2808 district road. Biomass clippings were done on 12 replicates for the control section (untreated section) of the road, as well as 12 replicates on all road sections covered with topsoil, irrespective of topsoil or application type (Diener 2018). Biomass was clipped within a 1 m² quadrat (following Bester 1988) in May 2017. The clippings were collected in paper bags and allowed to air-dry in the sun for 48 hours before weighing. Similar biomass clippings were collected on SP11, differentiating between the two sections treated at different times (2015 and 2016 respectively). A one-way ANOVA was applied between the two treatments on the road as well as on SP11 separately, using Statistica 10 (STATISTICA 2013).

RESULTS

D2808

The five identified sections of the abandoned D2808 road (as described in Table 1) are depicted in Figure 3 (top), whilst the NDVI profiles of the same sections are depicted in Figure 3 (bottom).

The RGB image (Figure 3 top) clearly indicates the unvegetated control section. The same road section shows partially white in the NDVI (Figure 3 bottom), which indicates that the glare from the unvegetated, white road surface, combined with a high sun elevation, was too intense for the camera sensor to provide reliable values.

The MSAVI2 results were very similar to the NDVI, except that differences were more difficult to detect. This confirms the problem described by Huete (1988) and Qi et al. (1994) that the SAVI and MSAVI lose

Table 3: Segments identified along the reclaimed slope of the waste rock dump, with their treatment. Positions are given as UTM Zone 33S co-ordinates.

| | North-western extent | South-eastern extent | Length (m) | Treatment |
|---------------------|----------------------------------|----------------------|------------|--|
| WRD2015 | 718497.9, 7789992.6 | 718115.4, 7789553.7 | 316.6 | Topsoil from Otjikoto pit, covered December 2015 |
| Southern upper dump | Adjacent (north-east of) WRD2015 | | | Natural vegetation establishment, no intervention |
| WRD2016 | 718115.4, 7789553.7 | 718088.9, 7789255.7 | 579.0 | Topsoil from Wolfshag pit, covered December 2016 to January 2017 |
| Northern upper dump | Adjacent (north-east of) WRD2016 | | | Control, freshly levelled and unvegetated, no intervention |

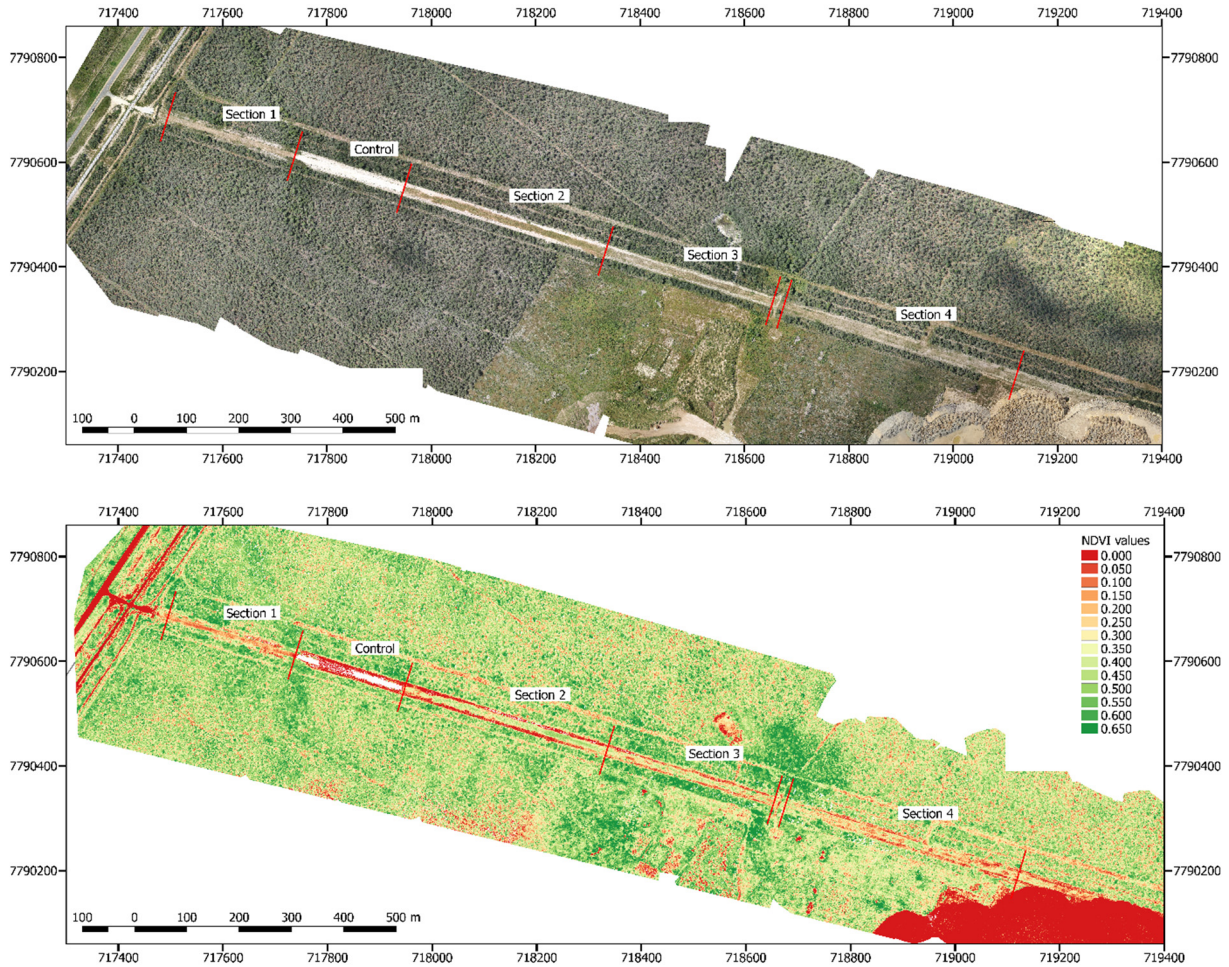


Figure 3: Aerial view of the abandoned section of the D2808 road. Various sections identified and described are indicated. Top: RGB image, bottom: NDVI image.

some information compared to NDVI. For this reason, the MSAVI2 was not further regarded.

The NDVI cross section values for the unreclaimed control contrast the elevated values represented by the undisturbed vegetated areas starting ca 13 m from the centre of the road in either direction, followed by a reduction in vegetation on the road verges (ca 5 to 13 m from the road centre) to the calcrete gravel compacted road surface (ca 4.5 to 5 m to either side from the road centre) (Figure 4). Relative success of revegetation of the road surface in sections 1 to 4 is illustrated by the difference in the average NDVI value between the unreclaimed road surface (control) and the average value of each section within 5 m of the road centre. It shows section 2 to have most successfully revegetated (NVDI mean 0.373, SD 0.032). Sections 3 and 4 produced lower average NDVI values (section 3 NDVI mean 0.323, SD 0.021; section 4 NDVI mean 0.273, SD 0.032) than section 2, but higher than section 1 (NDVI mean 0.189, SD 0.058), which was ripped, with an uneven, thin spread of topsoil. This is also partially confirmed

by the standing dry biomass measurements (Figure 5) which were significantly higher in sections 2, 3, and 4 than in road section 1 which was ripped but not topsoiled $F(1.94)=29.99, p<0.001$.

Figure 3 clearly indicates that the road verge (ca 4.5 to 13 m from the road centre) was not reclaimed – resulting in consistently lower NDVI values than the ripped and soil-covered road surface, and even the section of road which was ripped but not soil-covered. This supports the findings of various studies and guidance documents on reclamation and rehabilitation (Sheoran et al. 2010, Zhang et al. 2015).

Waste Rock Dump

The waste rock dump terrace slope rehabilitated in 2016 (WRD2016) (Table 3) shows a fairly dense vegetation cover along the upper 10 m of the terrace (NDVI mean 0.514, SD 0.134) (Figures 6 right and 7).

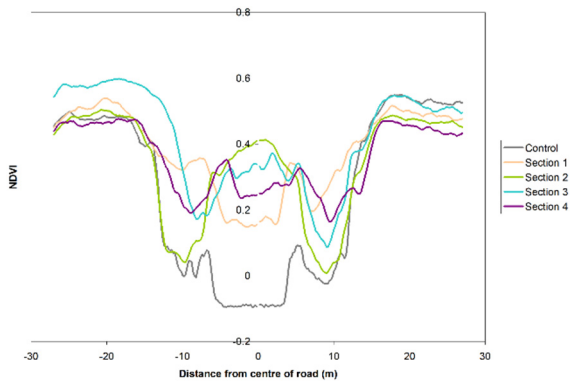


Figure 4: NDVI profile (cross sectional) for the five sections of the abandoned D2808 road.

These NDVI values are comparable to those of nearby natural vegetation surrounding the rehabilitated road (compare Figure 4 to Figure 7), indicating a similar density in vegetative ground cover. This vegetation cover is dominated by naturally established dense stands of *Stipagrostis hirtigluma* interspersed by other grass species (own observations). There is however an evident decline in vegetation cover from the top of the slope to the bottom. This is indicative of either an uneven spread of the topsoil from top to bottom, or erosion of the lower slopes, both phenomena common in waste rock rehabilitation sites (Sheoran et al. 2010). Section WRD2015 (Table 3) shows a highly uneven vegetative cover with sections of bare ground clearly

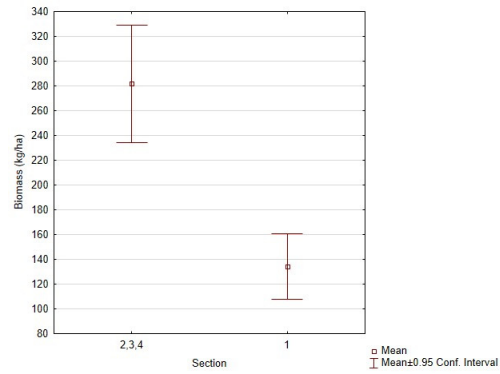


Figure 5: Field measured standing dry plant biomass ($n=12$) for road sections (within 2 m if the road centre)

visible (Figure 6 left). The upper slope area seems to be less vegetated than similar parts of the 2016 treatment, but the bottom slope shows more dense vegetation cover. This is indicative of erosion of the topsoil which has accumulated at the lower slope following three rainfall seasons. Signs of erosion are widespread along this section.

Two leguminose shrub species, *Dichrostachys cinerea* and *Mundulea sericea*, were observed on the SP11 waste rock dump, both in the WRD2015 and WRD2016 sections. Visual inspection of the aerial images revealed a greyish shrub on the lower slopes of SP11, which could be *Dichrostachys cinerea*.

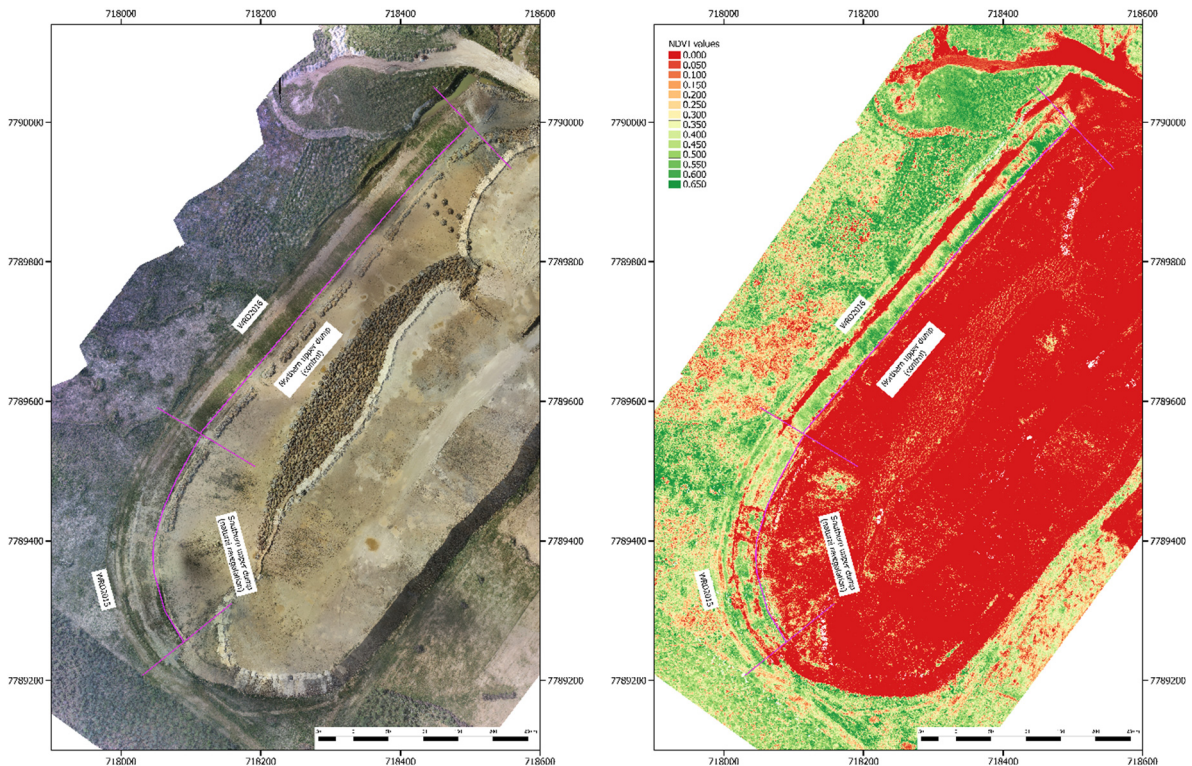


Figure 6: Aerial view of the reclaimed SP11 waste rock dump. Various sections identified and described, as well as the upper edge of the reclaimed slope, are indicated. Left: RGB image, right: NDVI image.

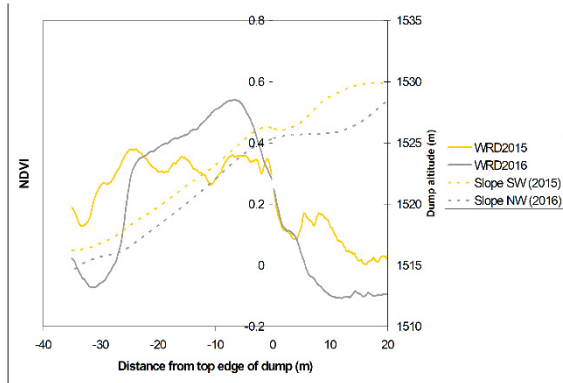


Figure 7: NDVI profile for the reclaimed waste rock dump slope. The respective dump slope altitude is indicated as thin dashed lines for reference purposes (not to scale).

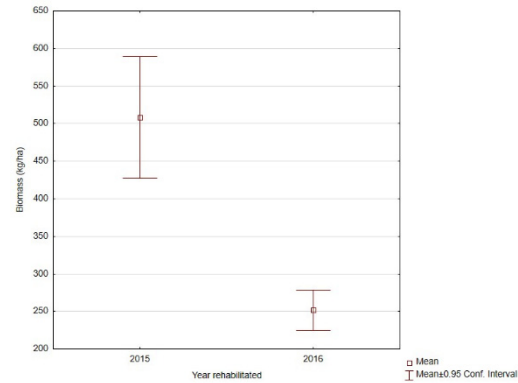


Figure 8: Field measured standing dry plant biomass for the portion of the SP11 terrace rehabilitated in 2015 compared to the portion rehabilitated in 2016. (n=12)

Overall standing plant biomass was significantly higher $F(1,94)=36.69$, $p<0.001$ for the two-year-old rehabilitated area (WRD2015) than the one-year-old rehabilitated area (WRD2016) (Figure 8). This was in part attributed to the relatively young establishment of grasses (one season) within the WRD2016 section, as well as the uneven distribution from top to bottom as evident in Figure 8. Monitoring data also indicate a weak early-season establishment on WRD2016 compared to the already established grass sward of WRD2015. This was however reversed, with better and more stable ground cover on WRD2016 than on WRD2015 later during the season (July and November 2017 surveys).

DISCUSSION

UAVs have become a useful tool in vegetation monitoring (Rasmussen et al. 2013, Getzin et al. 2014, Cruzan et al. 2016, Cunliffe et al. 2016, Müllerová et al. 2017, Oldeland et al. 2017), although scientists often turn to it for its popularity rather than its applicability (Freeman & Freeland 2015). In this study it was found particularly useful in detecting micro-level differences (at a spatial resolution of less than 5 cm) in a seemingly homogenous area. Within an active mining area, it was possible for the observer to remain at a safe distance from machinery and potential health (dust and noise) impacts. For this reason UAV monitoring has also been selected for e.g. forest fires (Casbeer et al. 2005), gas pipelines and highway traffic monitoring (Ro et al. 2007).

The study was able to comparatively determine vegetation establishment success among ad-hoc rehabilitation treatments applied on the mine. It is, however, impossible to comment on whether the rehabilitation in general, or certain treatments are effective in terms of Otjikoto Mine’s environmental management commitments because of the lack of a detailed rehabilitation plan. The mine has chosen instead to develop a broader rehabilitation framework (SLR 2014), which does not specify rehabilitation

methods or provide rehabilitation indicators or targets. Best practice suggests that a mine rehabilitation plan with clear definition of rehabilitation methods and monitoring targets is key to guiding and tracking rehabilitation progress (Cook 1976, Ludwig et al. 2003, Thompson & Thompson 2004).

Natural revegetation is evident on the top of the southern part of the dump (Figure 5), but is slow in establishment. This is consistent with findings by Martínez-Ruiz et al. (2007) and Valente et al. (2012), requiring interventions to improve establishment and further natural development. A basic intervention is the spreading of topsoil over the actual waste rock, as applied at the Otjikoto mine (Gilman et al. 1985, Maiti & Maiti 2015). Soil amelioration can be achieved by applying fertilizer (Tordoff et al. 2000, Cooke & Johnson 2002, Mendez & Maier 2008, Sheoran et al. 2010), mixing the poor-quality topsoil with biochar (i.e. ‘fines’ from the charcoal industry) (Beesley et al. 2011, Artiola et al. 2012, Paz-Ferreiro et al. 2014), or alternatively spreading biosolids on top of the applied topsoil. Such biosolids could be sewerage sludge, manure or even wood chips (produced from cleared shrubs in the bush-encroached surroundings) (Cooke & Johnson 2002, Sheoran et al. 2010). Especially sewerage sludge, but also wood chips, will have a fertilizing effect on the topsoil, whilst biochar improves the organic carbon content, the overall soils structure and also serves as a filter for unwanted phytotoxins from the soils. Many of these methods require adequate soil moisture and should be tested at a small scale within the semi-arid savanna rainfall regime.

Topsoil is prone to denitrification during storage, whilst other soil nutrients (especially phosphorous) are also rather limited (Sheoran et al. 2010). Because of this, inoculations with arbuscular mycorrhizal fungi as well as rhizobia are recommended (Bell et al. 2003, Lucy et al. 2004, Sheoran et al. 2010). Rhizobia will assist the newly established vegetative

cover to take up mineral nutrients, and also to manage any heavy metal residues in the dumps (Calvaruso et al. 2006, Mendez & Maier 2008). This is expected to be especially important in the rehabilitation of tailings dumps, but should be trialled first to assess its effectiveness.

The study indicated that slope erosion is a challenge which rehabilitation encounters on the SP11 waste rock dump. Slope rehabilitation commonly encounters erosion as a challenge. Research into slope design to reduce erosion is plentiful (Evans et al. 2000, Hancock et al. 2003, Martín-Duque et al. 2010). Terrace length and slope angle are two factors that are commonly considered. This has resulted in the mining company selecting the 18° slope and 20 m slope length sections between benches (SLR 2012). Our observations in Figures 5 and 6, however, indicate that erosion is a major factor over the short two-year period already. Classic slope design has been found to favour slope instability and water erosion (Martín-Duque et al. 2010), and geomorphic natural reclamation models are progressively more favoured (Hancock et al. 2003, Martín-Duque et al. 2010). Means of reducing rainfall runoff along the 20 m slope are recommended. Techniques such as active revegetation with a nursing crop (Tanner et al. 1986), provision of mulch (Bradshaw 2000) and ungulate hoof action (Savory 1988) should be investigated.

Establishment of a permanent vegetation cover is essential in order to stabilise the waste rock dump, preventing wind- and water erosion and potential contamination of the surrounding area by undesired, potentially toxic minerals washed down from the dump (Tordoff et al. 2000, Wong 2003, Mendez & Maier 2008). Perennial vegetation cover will be preferred, as it protects the covering soil best from wind- and water erosion. Deep-rooted trees have a special role to play in stabilisation (Gilman et al. 1985, Nilaweera & Nutalaya 1999, Mendez & Maier 2008, Stokes et al. 2009). As the topsoil available is limited (due to the very shallow A-horizon of the mollic leptosols), only a relatively thin layer is spread onto the dumps at Otjikoto Mine. The topsoil is also of fairly poor quality, with a high pH similar to the rock substrate within the waste rock dump. The natural establishment of *Dichrostachys cinerea* and *Mundulea sericea* on the waste rock dump indicates a high potential for these species to colonise these habitats and provide the first stabilisation of the spread topsoil and serve as an initial nursing plant for other species (Tanner et al. 1986). *Dichrostachys cinerea* is a known invader, favouring disturbed soils (Bell & Van Staden 1993, Moleele et al. 2002, De Klerk 2004, Mannheimer & Curtis 2009), and its seeds survive well in stored soils. As a matter of fact, burial of the seeds in soils for prolonged times favour their germination rate (Van Staden et al. 1994). These factors, however, make this species a potentially

double-edged sword, depending on the (yet to be determined) long-term rehabilitation goals for the waste rock dumps. It has the potential to outcompete all other vegetation (De Klerk 2004), reducing biodiversity on the rehabilitated area, but can also result in a stable slope with sustainable plant growth (Wakeling & Bond 2007, Stokes et al. 2009). *Mundulea sericea* could be an important keystone species, as it is leguminose and will enable nitrogen enrichment of these soils (Piha et al. 1995b).

This study did not consider specific species establishment, an important aspect to determine the effectiveness of rehabilitation more holistically (Ludwig et al. 2003, Thompson & Thompson 2004). It is also not an aspect currently considered by mine rehabilitation practices. The natural establishment of a dense sward of *Stipagrostis hirtigluma*, with some shrubs of *Dichrostachys cinerea* and *Mundulea sericea*, would fulfil basic reclamation requirements of establishing vegetative cover on the dump slopes. This would, however, not be a long-term sustainable goal, as *Stipagrostis hirtigluma* is short-lived, often even annual (Müller 2007) and *Dichrostachys cinerea* an aggressive invader (see above). The initial successful dense vegetative cover could be thus of short duration should *Dichrostachys cinerea* take over and replace the ground cover afforded by the present grass sward.

Establishment of an adequate perennial vegetation cover to restore ecological functionality will require targeted interventions to establish specific key species. An ideal situation will be the establishment of a mixture of native grasses and woody plants, avoiding exotic species and/or possible invaders (Sheoran et al. 2010). This can be achieved by targeted seeding and/or planting of saplings of indigenous species tolerant to high pH soils. In order to achieve long-term ecological rehabilitation, we recommend establishing the following species, based on their known habitat preferences in Namibia (see e.g. Mannheimer & Curtis 2009, Müller 2007, Strohbach & Kutuahuripa 2014): the dwarf shrub species *Eriocephalus luederitzianus*, *Leucosphaera bainesii* and *Ptychlobium biflorum* and the grass species *Enneapogon desvauxii*, *E. scoparius* and *Fingerhuthia africana*. *Catophractes alexandri* (a shrub, ca 2 m high), as well as common plains species of the surrounding area, including the leguminose species *Acacia mellifera* subsp. *detinens* and *A. luederitzii*, could potentially be established by direct reseeding, or by planting of saplings. The above combination of species would create an artificial ecosystem comparable to the surrounding plains and rocky outcrops.

Given the coarse, rather blocky nature of the substrate of the waste rock dump, the following Karstveld mountain tree species *Kirkia acuminata*, *Euphorbia*

guerichiana, *Moringa ovalifolia*, *Lannea discolor*, *Commiphora glaucescens* and/or *Berchemia discolor* can also be experimentally established. The grass species *Danthoniopsis dinteri* (annual) and *Triraphis ramosissima* (perennial) are also typical of these rocky habitats and are prolific seeders. If successful, all these species would create a woodland habitat not unlike the nearby Karstveld, allowing for an advanced state of ecological restoration. Near-natural restoration is unlikely to be achieved.

Further evaluation of the suitability of these species can be done using criteria discussed by Gilman et al. (1985), Mukhopadhyay et al. (2013), Nilaweera & Nutalaya (1999) and Schroth (1995), but also by experimental planting.

Soil moisture is critical for the successful establishment of tree and shrub species especially. Due to the steep, smooth nature of the dumps, and the thin topsoil layer, little rain water is held in the topsoil. Most will either run off, or percolate into the very porous waste rock dump. Improved water holding capacity can be achieved by the use of 'hydrogel' as part of the planting medium of saplings (Sarvaš et al. 2007). Watering saplings with drip irrigation is recommended by Cooke & Johnson (2002), Mendez & Maier (2008) and Tordoff et al. (2000). Such irrigation should, however, be limited by cost and water availability, and limited to only the establishment phase of the saplings (i.e. one or two seasons only) to avoid dependency. In the long-term, rainwater harvesting techniques, either through benching (Piha et al. 1995a, Wong 2003), or through construction of contoured weirs along the slope (Vohland & Barry 2009, Oweis 2016) will be more successful. Moreover, such measures will limit erosion of the applied topsoil. Erosion can also be reduced by shaping the dumps according to geomorphic principles, i.e. a convex upper slope and a concave bottom slope (Hancock et al. 2003). Excessive water damming on the top of the dump should be drained on specially constructed run-off channels (Wong 2003).

Overall, there are a large variety of techniques available for successful reclamation of the mine dumps at Otjikoto Mine. These range from reshaping the dumps to reduce erosion and improve water infiltration, to soil amelioration and targeted selection of species to be used for reclamation. What is urgently needed is a plan for rehabilitation (Cooke & Johnson 2002), as well as targeted experimentation with various interventions to promote establishment of a perennial vegetation cover. Evaluation of successful establishment should be done using multiple indicators, including annual NIR aerial photography, species composition as well as soil condition. As previously stated, these require an

initial development of a detailed rehabilitation plan (Ludwig et al. 2003, Thompson & Thompson 2004).

This study did not consider the chemical composition of the soils, or the interactions between the chemistry of the soil and underlying materials, but relied on the comparative physical rehabilitation treatments as applied by the mining company over the past two years.

IMPLICATIONS FOR PRACTICE

Most importantly, any measure of effectiveness of rehabilitation needs to be compared to a clear goal, targets and indicators.

Retrospective inspection of ad-hoc rehabilitation treatments can provide insights into determining the most effective methods for rehabilitation areas and predicting challenges which will face mine rehabilitation later in the lifecycle.

UAVs can be time and labour efficient tools for regular vegetation establishment monitoring at a high spatial resolution on rehabilitated sites. Their results do not, however, consider species composition, which is an important dimension to determine ecological functioning of rehabilitated areas.

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