

Success Indicators of Progressive Ecological Rehabilitation of Sites around a Tropical Highland Open Pit Mine

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Abstract

The plant species involved in the progressive rehabilitation around the Twangiza open gold mine in DR Congo were inventoried to establish their abundance and diversity. Their spatial growth patterns were mapped and described through NDVI on a 10 m Sentinel satellite imagery. Field data collection was based on transects and relevés. Soil physico-chemistry was evaluated. Multivariate cluster analysis was computed to describe associations. Tree species were planted in 2012 on barren land. Five years later, in 2016, the very dense vegetation class already reached 10.8% and a twofold increment in 2023 (22%). The moderately dense vegetation category was already very high in 2016 and similarly in 2023 (24.1% - 25.9%). Results show that *Brachypodium retusum*, *Muhlenbergia capillaris*, *Cynodon dactylon*, and *Melastoma malabathricum* were the most frequent herbaceous plant species (5% - 10% cover). Among the planted trees, the highest cover was performed by *Pinus patula* (30%). *Casuarina equisetifolia* and *Grevillea robusta* achieved about 10% - 12% cover. *Hagenia abyssinica*, a native plant, was among the species that achieved a moderate cover. *Prunus africana*, *Jacaranda mimosifolia* and *Acacia mearnsii* achieved a relatively lower cover. *Ficus thonningii* is the largest tree (max 280 cm collar diameter). *Acacia melanoxylon* and *Maesopsis eminii* were large trees as well (163 - 175 cm). The tallest trees were respectively *Maesopsis eminii*, *Cedrela serrulata* and *Acacia melanoxylon* (35 - 45 m) followed by *Ficus thonningii*. Among the shrubs, the highest cover was achieved by *Erica scoparia* (26%) followed by *Sambucus canadiensis*, *Pycnostachys erici-rosenii*, *Blechnum cordatum*, and *Quercus lusitanica*. The vegetation encountered at Twangiza during the baseline study back in 2008 was generally disturbed and secondary. Evidences of soil improvement are given too: Organic carbon, total nitrogen, exchangeable magnesium, absorbable potassium, exchangeable sodium, calcium

and absorbable phosphorus are strongly boosted. Animal recolonization is successfully proven separately (Basima et al., 2025a). Grazing land for cattle is the main ecosystem service in the rehabilitated zone (66%). Most cattle are composed of cows, goats and sheep which graze on grass (*Muhlebergia capillaris*, *Cynodon dactylon*, *Brachypodium retusum*) that was planted for erosion control and soil cover as part of the rehabilitation exercise from the vicinities.

Keywords

Mining, Ecological Rehabilitation, Plant Growth Pattern, Soil Improvement

1. Introduction

It is common knowledge that the mining of mineral resources causes serious damage to land and significant pressure on the ecological environment. Zeng et al. (2018) even turned to the famous issue of Resource Curse hypothesis which holds that, in resource-rich regions or countries, resources have not brought sufficient impetus to economic growth and have even become a limitation for regional economic development and the ecological and environmental protection undertakings. Therefore, ecological restoration has become an essential research thematic. Shao et al. (2023) found that, currently, there are two major concerns of land reclamation and ecological restoration: one is heavy metal pollution caused by mining, and the other is ecological restoration in mining areas, especially soil reconstruction and vegetation restoration.

According to Carabassa et al. (2019), ecological restoration is defined by The International Society for Ecological Restoration as the process of assisting in the recovery of an ecosystem that has been degraded, damaged or destroyed (Metsaranta & Bhatti, 2016), in order to retrieve its environmental functions and ecosystem services.

Mine reclamation is the process of restoring and rehabilitating former mining lands for reuse or returning them to their natural condition after mining activities are completed or halted. The primary goal of mine reclamation is to reduce the negative environmental impacts of mining and restore the land for various purposes such as agriculture, forestry, recreation, or nature conservation. The rehabilitation involves landscape restoration and water quality improvement, including the maintenance of sustainable drainage systems. This can help reduce water pollution by controlling surface water flow and minimizing soil erosion and sediment runoff into rivers and lakes. It implies wildlife habitat rehabilitation to increase biodiversity and boost carbon storage, helping mitigate the impact of climate change. There are also some economic benefits to forestry and water and soil conservation. Mine reclamation includes efforts to manage soil pollution and reduce dust and air pollution control (Mucina et al., 2019). These implied intentions include the concepts of minimization of loss of land use capability and of net benefit to society (Coaltech, 2007).

About the objectives of rehabilitation internationally, there seem to be three schools of thought: a) providing the end product requested by the affected communities, rather than focusing on the previous status quo; b) restoration of previous land use capability, especially when mining occurs on land with high agricultural potential; c) no net loss of biodiversity. Practically, rehabilitation objectives usually contain elements of all three approaches. Historically, restoration of land capability has been the key factor (Coaltech, 2007). The most important rehabilitation goal must be to achieve revegetation of the degraded area. The aim should be to progressively rehabilitate an area and not to wait until only after the mining has been completed (Schmidt, 2002). Moreover, the ecological restoration and renewal development mode is a multidisciplinary comprehensive control project involving mining, geology, surveying, ecology, environment, land use, and planning (Chen, 2018).

With respect to its importance, ecological restoration of mining areas is a research focus. Shao et al. (2023), who analyzed 2357 articles to explore the development of land reclamation and ecological restoration research from 1990 to 2022, found two research hotspots, one surrounding heavy metal pollution and the other focusing on the ecological restoration of mining areas. Thematic evolution analysis shows that, for more than 30 years, mine drainage and heavy metal pollution treatment, soil reconstruction (soil profile reconstruction and soil improvement), and vegetation restoration have been the focus of research.

Nontobeko (2020) rightly noted that rehabilitation is very costly; it is therefore very important that the efforts put into rehabilitation yield successful outcomes. Internationally, the International Council on Mining and Metals (ICMM) has published a few guidelines, including Good Practice Guidance for Mining and Biodiversity (ICMM, 2006), Planning for Integrated Mine Closure: Toolkit (ICMM, 2008), and Integrated Mine Closure: Good Practice Guide (ICMM, 2019), which is an update of the 2008 toolkit.

The present paper focuses on a progressive ecological rehabilitation that has been underway since 2010 at Twangiza, an industrial highland long-term open-pit gold mine, with activities since 1938, including small-scale mining, in the eastern part of the DR Congo. This tropical area is characterized by high yearly rainfall (1500 mm) with two seasons, in a mountainous topography with steep slopes (1900 - 2700 m asl). The open pit implies excavations. The ecological rehabilitation is expected to improve the water quality and quantity and to reduce dust and erosion. It is also expected to provide services to the community in terms of firewood, grazing pastures, and medicinal plant supply. The afforestation amounts to 100 ha within the site and at least 757 ha within the general communities.

In fact, ICCM guidelines are equally applicable to small and big mining companies (ICMM, 2019). Most well-established mining companies also have their own in-house rehabilitation guidelines, as is the case here.

So, at the onset, the goals of the progressive rehabilitation project were essentially:

a) To ensure all the 40 km long roads that were opened from Butuza to Twangiza (and later on to the Cinjira resettlement village) are covered by trees. The berms

were being installed for safety reasons, grassed by soil-fixing plants for erosion control and reduction of landslides that were deteriorating the road access so often.

b) To plant grasses over all the slopes generated by the opening of spaces for the establishment of infrastructure like camps, the process plant, and the Cinjira resettlement village with its platform accesses;

c) To sensitize the general community on the importance of tree planting by gradually changing their old mentality and developing their skills and capacity through the experience that will be gained over time;

d) To draw knowledge on species adaptation and growth rate in order for the mine to be prepared to address the mandatory and regulatory rehabilitation project as required by the Environmental and Social Management Plan, as this is believed to be less costly, time efficient, and with less groping;

e) To conduct a progressive rehabilitation by pricking local native plant species that may grow under exotic species canopy.

Now it is useful to investigate the vegetation dynamics of this ecological restoration. This allows us to assess the success of this project and draw lessons for improvement. It will also serve as an environmental education material locally and in similar conditions. This would also be useful to champion a new law on mining restoration in the DRC and as guidance for other mining companies operating in similar conditions.

The aim of this study is to assess the success of ongoing ecological rehabilitation as a way to mitigate environmental issues. The specific objectives are the following:

- 1) Make an inventory of the vegetation species involved in the rehabilitation project and their characteristics (abundance, diversity, and cover);
- 2) Identify the species associations and their associated system services;
- 3) Map the spatial growth patterns through the NDVI analysis;
- 4) Analyze physico-chemical soil properties for the soil improvement assessment;
- 5) Identify the major community uses and specific threats associated with the rehabilitation project.

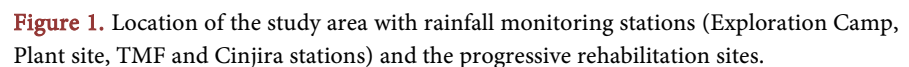
2. Material and Methods

2.1. Study Area

The Twangiza open-pit gold mine is located in the District of Mwenga, South Kivu Province, DR Congo, at 45 km south-southwest of Bukavu city, the capital of the South Kivu Province. The road access from Bukavu is 85 km, through the national road (RN2). The lowest average temperature is 13 degrees Celsius, while the maximum is 22 degrees with a hilly topography averaging between 2000 and 2500 m asl. However, the highest close by hill goes up to 3250 m asl.

The mine area consists of a dense network of steep hills and valleys that result in a dense stream network, draining in a northwesterly direction. The ridge that the mine occupies is surrounded by the Mwana River to the west and the Lulimbohwe River to the east. Both the Mwana and Lulimbohwe are fast-flowing, perennial, rock mountain rivers that converge immediately to the north of the explo-

The following sites were availed by the Twangiza Mine Project for progressive ecological rehabilitation: KRV, EC, ASMC, CSC, OPSC, TOPSC, PSS and BLY as shown in **Figure 1** and described in **Table 1**.



Site name	Highest Point			Medium Point			Lowest Point					
	Easting	Northing	Elevation (m)	Easting	Northing	Elevation (m)	Easting	Northing	Elevation (m)	Surface area (m²)	Slope (%)	Slope (°)
PSS	694220.614	9681750.800	2378.00	694272.623	9682171.720	2322.00	694256.12	9682390.10	2252.44	98787.175	51.98	27.46
BGS	693974.229	9682331.059	2329.00	693961.100	9682446.900	2298.30	694068.62	9682370.73	2278.67	17642.738	55.01	28.82
OPSC	693792.300	9681416.400	2331.30	693623.200	9681527.900	2294.70	693563.90	9681436.70	2239.00	62854.328	49.55	26.36
TOPSC	694132.800	9681323.200	2524.80	693944.600	9681407.500	2406.40	693789.50	9681413.60	2328.40	145093.265	46.21	24.80
CSC	694615.110	9680857.000	2690.41	694433.500	9680668.540	2584.63	694251.03	9680436.84	2462.36	118624.113	58.86	30.48
ASMC	694303.590	9681247.380	2584.28	694383.620	9681449.650	2437.57	694435.03	9681773.31	2246.72	262783.476	62.11	31.85
EC	691943.400	9686181.870	1835.93	691794.220	9686941.640	1810.13	691705.79	9686397.32	1781.35	67665.128	20.46	11.57
KRV	691734.294	9685847.358	1863.42	691734.374	9686008.943	1819.27	691613.02	9686089.55	1757.13	104478.813	30.17	16.79
BLY	691470.900	9686337.730	1800.26	691365.320	9686319.030	1789.01	691705.79	9686397.32	1781.35	67665.128	72.97	36.12

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2.2. Nurseries and Planting

Three nurseries were established in 2010, while the preparation of the land by plowing, seed planting, pricking, and maintenance of tree seedlings and herbaceous plant species of special importance, and erosion control via gabion baskets were being established. The following tree species were used in this program: *Acrocarpus fraxinifolius*, *Adansonia digitata*, *Albizia adianthifolia*, *Calliandra calothyrsus*, *Casuarina equisetifolia*, *Cedrela serrulata*, *Grevillea robusta*, *Hagenia abyssinica*, *Jacaranda mimosifolia*, *Leucaena glauca*, *Maesopsis eminii*, *Markhamia lutea*, *Moringa oleifera*, *Pinus patula*, *Podocarpus usambarensis*, *Prunus africana*, *Senna notabilis*, *Spathodea campanulata*, *Terminalia* spp. and *Theobroma cacao*. The germination status was assessed over a 3-year period. *Muhlebergia capillaris*, *Brachypodium retusum*, *Cynodon dactylon* and *Buddleja globosa* were deliberately chosen for grassing berms, slopes and selected areas for their importance in erosion control.

2.3. The Progressive Rehabilitation Support Infrastructure

The infrastructure was developed to support the progressive rehabilitation including concrete drains, HDPE pipe drains, gabion baskets for side walls and roads support, reused tires for slope stabilization and concrete masonry. These are shown in **Figure 2**.



Figure 2. Gabion baskets in support of the main access road (A) and a wall side (B); tires being positioned to support an access road with drainage (C) and concrete side drains on the wall side (D).

The topographic characteristics of the progressive ecological rehabilitation sites are presented in **Table 1**, with more attributes such as surface area, elevation, and

percentage slope.

2.4. Data Collection

2.4.1. Vegetation Species and Characteristics

Vegetation species that grew at the 9 progressive rehabilitation sites (listed in **Table 1**) were identified through an inventory based on a transect technique. Three quadrats were selected per site to allow for adequate representation with a 15 m × 15 m (225 sqm) surface area. The average data was encoded in a spreadsheet covering the following information: species presence/absence, dominance, vegetation type (tree, shrub, herbaceous plants), percentage cover in the quadrat, tree height and its root collar diameter (in cm).

Jasper et al. (2003) recommended the evaluation of forest productivity from the sampling of tree diameter growth. Changes in tree population structure and species composition provide insight into the rate and direction of development. Obvious importance to the community and threats were also considered. The identification of the specimen collected in the field was done at the Herbarium of the Faculty of Sciences of the Université Officielle de Bukavu (UOB) and of the Centre de Recherche en Sciences Naturelles (CRSN/Lwiro).

2.4.2. Vegetation Dynamics Analysis

The estimation of vegetation cover changes was conducted using the normalized difference vegetation index (NDVI) from 10 m Sentinel satellite imagery collected in August 2016 and October 2023 in order to assess the vegetation dynamics. NDVI values range from −1.0 to 1.0 and represent vegetation density and vigor of the vegetation, with negative values corresponding to surfaces other than plant cover, such as snow cover, water, or clouds, for which the red reflectance is greater than that of the near-infrared. For bare ground, reflectance is of roughly the same order of magnitude in the red and near-infrared; the NDVI values are close to 0. Vegetation formations, on the other hand, have positive NDVI values, generally between 0.1 and 0.7. The highest values correspond to the densest vegetation. For the Twangiza area, the 10m resolution strips taken in August 2016 and October 2023 were used to determine this index using the formula $NDV = (B8 - B4)/(B8 + B4)$; where Band 8 represents the near-infrared light and Band 4 represents the red light.

2.5. Soil Sampling and Laboratory Analyses

Initial soil samples were taken randomly from 9 rehabilitation sites and 3 non-rehabilitated sites at 20 cm-depth. From each block, 3 samples were taken and bulked to obtain one composite sample for each block. These samples were then subjected to analysis after air-drying, crushing and sieving through a 2 mm sieve. Physical and chemical properties were determined at the Soil Laboratory of the Université Catholique de Bukavu, following specific procedures for each parameter; i.e bulk density, moisture content, pH, organic carbon, total nitrogen, available phosphorus, calcium and magnesium, exchangeable cations (Ca, Mg, K and Na).

Interpretation guides for soil chemical parameters were used for organic carbon, Phosphorus (ppm), total nitrogen (%), Potassium (meq/100g), Calcium (meq/100g); Magnesium (meq/100g) and Sodium (meq/100g), CEC (meq/100g), pH (1:5 H₂O) (Okalebo et al., 1993; Landon, 2014).

2.6. Data Analysis

Mucina et al. (2019) performed Multivariate comparative (cluster) analysis on a species-by-site matrix to measure the similarity between sites based on the presence or absence of species. A clearly legible dendrogram was produced to illustrate the similarities between the vegetation units that have been identified.

3. Results

3.1. Species Abundance and Diversity

3.1.1. Herbaceous Plant Species Cover

The following grasses had the highest cover (50% - 80%): *Plantago subulata*, *Muhlenbergia capillaris*, *Campylopus introflexus*, *Brachypodium retusum*, *Paspalum notatum*, *Lycopodium clavatum*, *Cenchrus clandestinus*, *Achillea ageratum*, *Cynodon dactylon*, *Mitracarpus hirtus*, *Pteridium aquilinum*, and *Lycopodium annotinum*. These are shown in Figure 3.

The grasses which had moderate cover included *Vernonia baldwinii*, *Ruellia prostata*, *Spermacoce ocymifolia*, *Maesa lanceolata*, *Phytolacca dodecandra*, *Achyranthes aspera*, *Rubus fruticosus*, *Bidens pilosa*, *Solanum mauritianum*, *Buddleja globosa*, *Artemisia dracunculus*, *Hibiscus rosa-sinensis*, *Melastoma malabathricum*, *Acacia mearnsii*, *Dicranopteris linearis*, *Rubus spp.*, *Dichranopteris linearis*, and *Cyperus spp.*

The most dominant grass species were *Plantago subulata*, *Paspalum notatum*, *Brachypodium retusum*, and *Muhlenbergia capillaris* followed by *Lycopodium clavatum*, *Cynodon dactylon*, *Vernonia baldwinii*, *Campylopus introflexus*, *Cenchrus clandestinus*, *Mitracarpus hirtus*, *Pteridium aquilinum*, *Achillea ageratum*, *Lycopodium annotinum*, *Escallonia rubra*, *Spermacoce ocymifolia*, as shown in Figure 4.

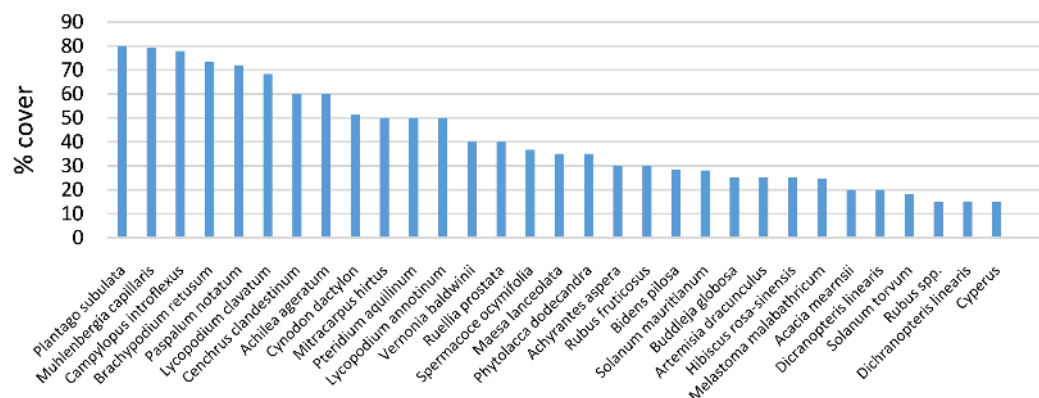


Figure 3. Percentage cover for Herbaceous plants (least selected cover $\geq 15\%$).

3.1.2. Herbaceous Plant Species Abundance and Diversity

a) Herbaceous plants presence-absence

Herbaceous plant species diversity (S) was similar at most sites (15 - 20 species). Only PSSQ was exceptional, reaching up to 35 species. Also, a distinct minimum number of species occurred at BLYQ (S = 5 species) as shown in **Table 2**.

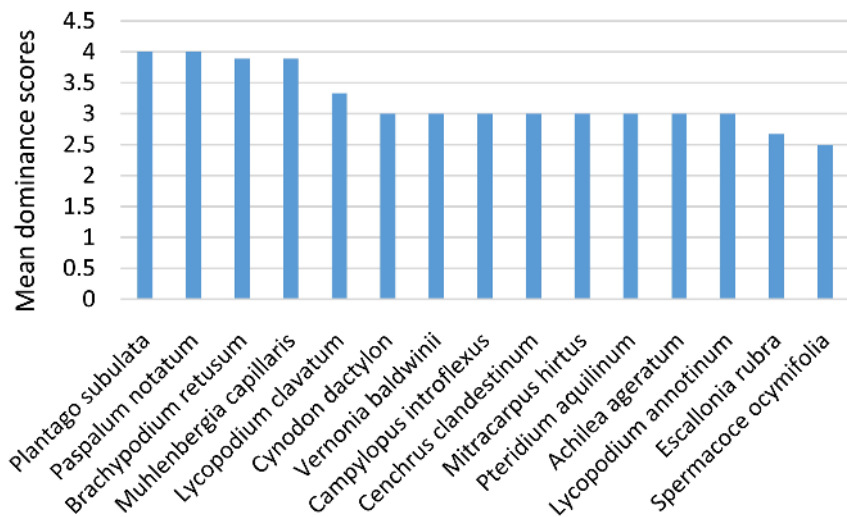


Figure 4. Dominance score for herbaceous plants.

Table 2. Similarity indices for presence-absence for herbaceous plants grass.

	BLYQ	BGSQ	BLYQ	BelowPSSQ	CSCQ	ECQ	OPSCQ	PSSQ	TOPSCQ
Taxa_S	4	13	13	14	18	16	14	34	17
Individuals	4	13	13	14	18	16	14	34	17
Dominance_D	0	0	0	0	0	0	0	0	0
Simpson_1-D	1	1	1	1	1	1	1	1	1
Shannon_H	1.76	3.03	3.03	3.10	3.36	3.24	3.10	4.01	3.30
Evenness_e^H/S	1.46	1.59	1.59	1.59	1.60	1.60	1.59	1.63	1.60
Brillouin	0.79	1.74	1.74	1.80	2.02	1.92	1.80	2.61	1.97
Menhinick	2.00	3.61	3.61	3.74	4.24	4.00	3.74	5.83	4.12
Margalef	2.16	4.68	4.68	4.93	5.88	5.41	4.93	9.36	5.65
Equitability_J	1.27	1.18	1.18	1.18	1.16	1.17	1.18	1.14	1.17
Fisher_alpha	0	0	0	0	0	0	0	0	0
Berger-Parker	0.25	0.08	0.08	0.07	0.06	0.06	0.07	0.03	0.06
Chao-1	8.5	85	85	98.5	162.5	128.5	98.5	578.5	145
iChao-1	8.5	85	85	98.5	162.5	128.5	98.5	578.5	145
ACE	8.5	85	85	98.5	162.5	128.5	98.5	578.5	145

*BLYQ: Bonded-Laydown Yard Quadrant; BGSQ: Boom Gate Slopes; BelowPSSQ: Below Plant Site Slopes; CSCQ: Cinjira Camp Saio; ECQ: Exploration Camp; OPSCQ: Operators' Camp; PSSQ: Plant Site Slopes; TOPSCQ: Top of Operators' Camp.

PSSQ was exceptional, probably due to the fact that the site was extensively grassed for erosion control, as the site received fill material from the process plant construction, and was less impacted by community plowing and farming as compared to OPSCQ, TOPSCQ which have similar conditions and with better soil fertility. PSSQ was less impacted by the community due to its proximity with the process plant, hence with regular movement of employees and security services.

b) Herbaceous plants abundance-dominance

The highest herbaceous plants abundance-dominance occurred at BLYQ, followed by BGSQ. Elsewhere, the abundance-dominance was similar and lower. So, the equitability was highest at ECQ, followed by CSCQ, indicating that no species was dominating in abundances at those sites, unlike elsewhere.

3.1.3. Trees and Prostrate Shrubs

The highest cover was performed by *Pinus patula* (30%). *Casuarina equisetifolia* and *Grevillea robusta* achieved about 10% - 12% cover. *Hagenia abyssinica*, a native species, *Spathodea campanulata*, *Cupressus lusitanica* achieved a moderate cover. *Prunus africana*, *Jacaranda mimosifolia* and *Acacia mearnsii* achieved a relatively lower cover. The frequency of trees and prostrate shrubs in the progressive rehabilitation sites is presented in **Table 3**.

Table 3. Frequency of trees and prostrate shrubs in the progressive rehabilitation sites.

Trees	%	Shrubs	%
<i>Pinus patula</i>	30	<i>Hypericum revolutum</i>	4.3
<i>Grevillea robusta</i>	12	<i>Pycnostachys erici-rosenii</i>	8.7
<i>Casuarina equisetifolia</i>	10	<i>Sambucus canadiensis</i>	13
<i>Hagenia abyssinica</i>	6	<i>Vaccinium myrsinites</i>	4.3
<i>Spathodea campanulata</i>	6	<i>Blechnum cordatum</i>	8.7
<i>Cupressus lusitanica</i>	4	<i>Erica scoparia</i>	26.1
<i>Prunus africana</i>	4	<i>Tetradenia riparia</i>	4.3
<i>Persea americana</i>	2	<i>Quercus lusitanica</i>	8.7
<i>Ficus thonningii</i>	2	<i>Calliandra houstoniana</i>	4.3
<i>Jacaranda mimosifolia</i>	2	<i>Pulchea carolensis</i>	4.3
<i>Acacia mearnsii</i>	2	<i>Hibiscus surattensis</i>	0
<i>Acacia melanoxylon</i>	2	<i>Escallonia rubra</i>	0
		<i>Chamaecrista fasciculata</i>	0

Among the shrubs, the highest cover was achieved by *Erica scoparia* (26%) followed by *Sambucus canadiensis*, *Pycnostachys erici-rosenii*, *Blechnum cordatum*, *Quercus lusitanica*. *Hypericum revolutum*, *Vaccinium myrsinites*, *Tetradenia riparia*, *Calliandra houstoniana*, and *Pluchea carolinensis* had a relatively low cover. *Cupressus lusitanica*, *Eucalyptus* spp., and *Persea americana* were not planted during the rehabilitation exercise but were present in the region, planted by previous landowners, and have naturally propagated.

Among the trees, the most dominant species were *Grevillea robusta*, *Blechnum cordatum*, *Calliandra houstoniana*, *Pinus patula* and *Pycnostachys erici-rosenii* followed by *Acacia mearnsii*, *Cordia africana*, *Quercus tomentella*, *Erica scoparia*, *Macaranga tanarius*, *Nuxia congesta*, *Quercus lusitanica*, *Vernonia amygdalina* and *Casuarina equisetifolia* as shown in **Figure 5**.

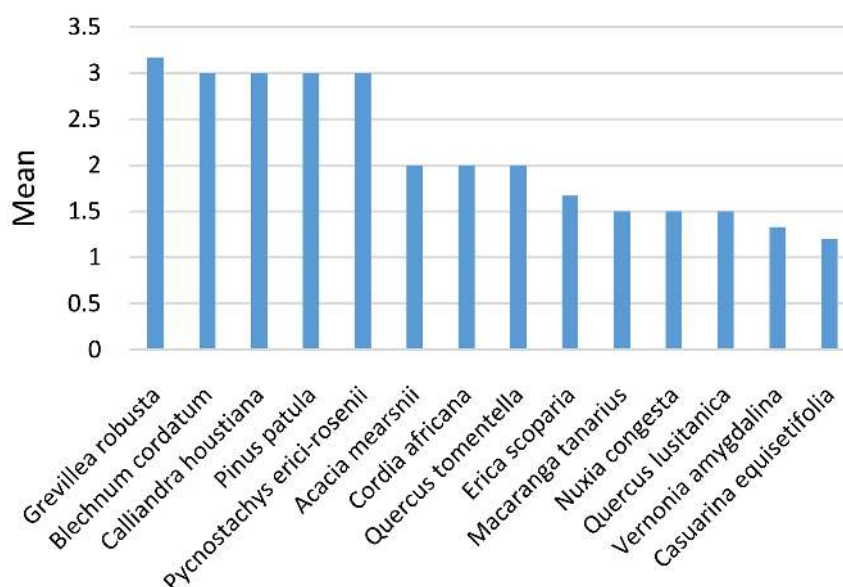


Figure 5. Tree species dominance in the progressive rehabilitation sites.

a) Trees presence-absence

The lowest tree species diversity occurred at the site BLYQ, followed by BGSQ ($S = 5 - 7$) as shown on **Table 4**. The diversity is moderate (average) at Below PSSQ, ECQ, PSSQ and TOPSCQ ($S = 7 - 9$). The highest tree species diversity was observed at BLYQ, followed by far with CSCQ and OPSCQ ($S = 11 - 13$). This trend is obviously confirmed Individuals (N) and the Shannon and the Brillouin and Fisher's Alpha and the Chao-1 and ACE.

The Simpson_1D index indicates higher and similar levels of diversity in TOPSCQ, BGSQ, OPSCQ, PSSQ, ECQ, CSCQ and BLYQ ($D = 0.69 - 0.74$). A relatively lower diversity is observed in BLYQ ($D = 0.80$). The Shannon_H index indicates a higher diversity in BLYQ ($H = 2.06$) and similar diversity levels elsewhere ($H = 1.48 - 1.84$).

The degree of diversity at the progressive ecological rehabilitation sites is presented in **Table 5**.

b) Trees abundance-dominance

Unlike the diversity of herbaceous plants which is very high at all of the ecological rehabilitation sites, that of trees and shrubs is low. The highest tree abundance-dominance was observed at BGSQ and TOPSCQ. OPSQ and PSSQ ranked in second order. CSCQ and ECQ had similar and moderate abundance-dominance. The lowest tree abundance-dominance was observed at BLYQ. Thus, the highest Equitability occurred BLYQ, where no few species whatsoever dominated

in abundance, unlike the other sites.

Table 4. Diversity indices for trees and shrubs regarding presence/absence.

	BLYQ	BGSQ	BLYQ	BelowPSSQ	CSCQ	ECQ	OPSCQ	PSSQ	TOPSCQ
Taxa_S	13	7	4	9	12	7	11	7	8
Individuals	30	50	6	30	88	16	42	30	30
Dominance_D	0.26	0.31	0.20	0.27	0.28	0.26	0.30	0.29	0.31
Simpson_1-D	0.74	0.69	0.80	0.73	0.72	0.74	0.70	0.71	0.69
Shannon_H	2.06	1.48	1.49	1.77	1.84	1.71	1.71	1.59	1.56
Evenness_e^H/S	0.60	0.63	1.11	0.65	0.52	0.79	0.50	0.70	0.60
Brillouin	1.45	1.25	0.80	1.33	1.59	1.14	1.32	1.23	1.18
Menhinick	2.37	0.99	1.63	1.64	1.28	1.75	1.70	1.28	1.46
Margalef	3.53	1.53	1.67	2.35	2.46	2.16	2.68	1.76	2.06
Equitability_J	0.80	0.76	1.08	0.81	0.74	0.88	0.71	0.82	0.75
Fisher_alpha	8.72	2.22	5.25	4.36	3.75	4.75	4.85	2.87	3.57
Berger-Parker	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Chao-1	66.17	7.49	6.5	10.45	12.49	16.38	38.33	7.322	12.83
iChao-1	66.17	8.96	6.875	11.58	14.02	17.39	40.19	8.207	20.08
ACE	110.8	8.791	11.6	13.82	12.78	22.04	51.95	8.658	25.75

Table 5. Degree of diversity at the various ecological rehabilitation sites (Fernando et al. 1998 classes and Chugani, 2025 for Margalef index).

Herbaceous plants	BGSQ	BLYQ	BelowPSSQ	CSCQ	ECQ	OPSCQ	PSSQ	TOPSCQ
Shannon_H	3.03	3.03	3.1	3.36	3.24	3.1	4.01	3.3
Shannon diversity class	high	high	high	high	high	high	very high	high
Simpson_1-D	1	1	1	1	1	1	1	1
Simpson diversity class	absolute (perfect)	absolute (perfect)	absolute (perfect)	absolute (perfect)	absolute (perfect)	absolute (perfect)	absolute (perfect)	absolute (perfect)
Margalef diversity class	high richness	high richness	high richness	exceptionally high	exceptionally high	high richness	exceptionally high	exceptionally high
Trees and shrubs								
Shannon_H	1.48	1.49	1.77	1.84	1.71	1.71	1.59	1.56
Shannon diversity class	very low	very low	very low	very low	very low	very low	very low	very low
Simpson_1-D	0.69	0.80	0.73	0.72	0.74	0.70	0.71	0.69
Simpson diversity class	moderately high	moderately high	moderately high	moderately high	moderately high	moderately high	moderately high	moderately high
Margalef diversity class	Low richness	Low richness	Moderate richness	Moderate richness	Moderate richness	Moderate richness	Low richness	Moderate richness

3.2. Species Associations and Functions

3.2.1. Overall Associations

The vegetation cover overall associations are presented in **Figure 6**.

3.2.2. Presence/Absence Clusters

With regards to the trees which achieved the highest covers, the highest co-occurrences (Morisita similarity = 0.50 - 0.87) were observed between ***Pinus patula***: *Muhlenbergia*, *Brachypodium retusum*, *Solanum mauritianum*, *Solanum torvum*, *Erica scoparia*. ***Grevillea robusta***: *Solanum mauritianum*, *Solanum torvum*, *Casuarina equisetifolia*, *Spathodea campanulata*. ***Casuarina equisetifolia***: *Grevillea robusta*, *Spathodea campanulata*. ***Hagenia abyssinica***: *Aeschynomene americana*, *Sambucus mexicana*, *Jacaranda mimosifolia*, *Paspalum notatum*, *Hibiscus*, *Myrianthus arboreus*, *Anthocleista grandiflora*, *Fallopia*, *Dracaena* spp., *Acacia mearnsii*. ***Spathodea campanulata***: *Grevillea robusta*, *Casuarina equisetifolia*, *Spermacoce ocymifolia*, *Pulchea carolensis*, *Jacaranda mimosifolia*, *Clerodendron chinense*, *Dryopteris cristata*, *Mitracarpus hirtus*, *Erythrina abyssinica*, *Senna spectabilis*, *Cedrela serrulata*. This is shown in **Figure 7**.

In terms of presence/absence of species at sites, the highest similarities are observed between the BLYQ and ECQ, OPSCQ, PSSQ, TOPSCQ. They are also

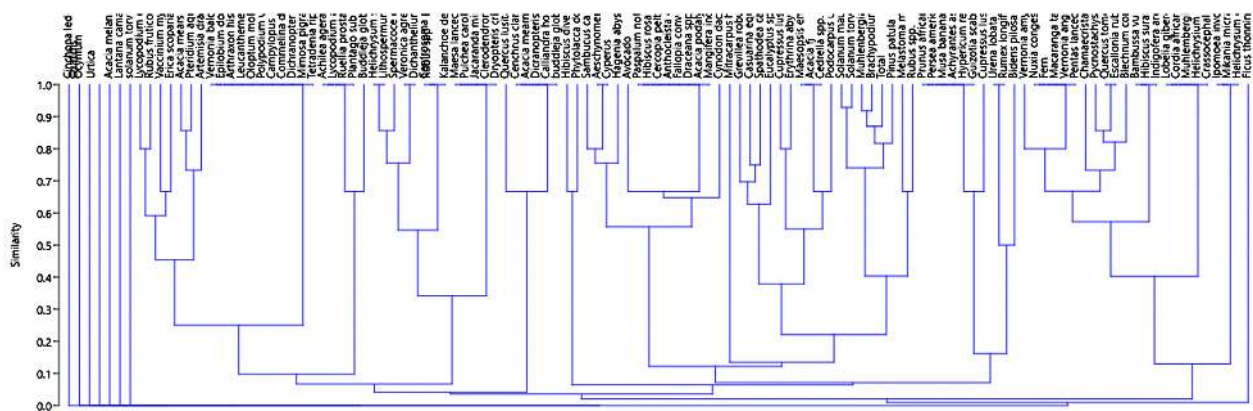


Figure 6. vegetation cover overall species association on the progressive rehabilitation sites.

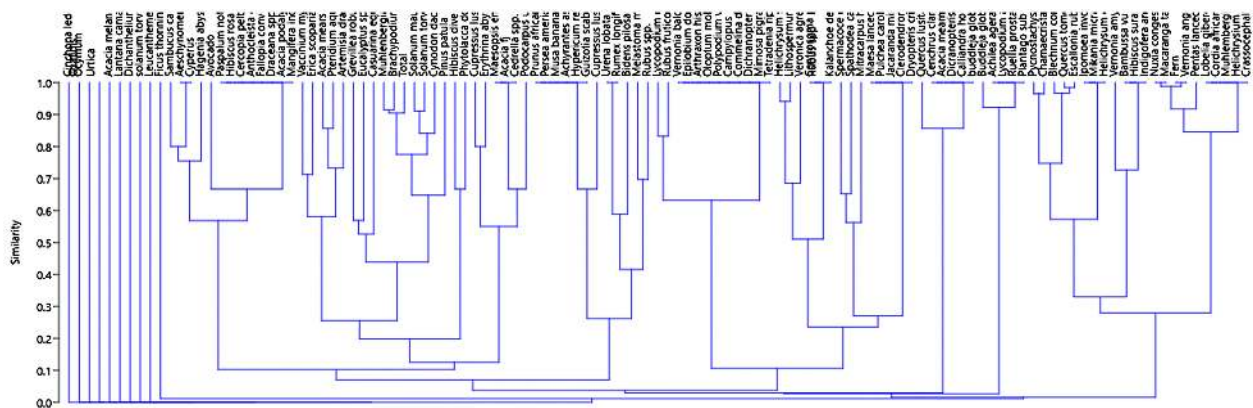


Figure 7. Morisita similarity index showing dominance clusters for the vegetation cover at the progressive rehabilitation sites.

observed between BelowPSSQ and OPSCQ, between ECQ and TOPSCQ, between OPSCQ and TOPSCQ and between PSSQ and ECQ.

3.2.3. Tree and Shrub Similarities

High similarities (>95%) were observed between *Bambusa vulgaris*, *Blechnum cordatum*, *Cordia africana*, *Lobelia giberroa*, *Macaranga tanarius*, *Nuxia congesta*, *Pychnostachys erici-rosenii*, *Quercus lusitanica* and *Vernonia amygdalina*. *Erica scoparia* and *Pinus patula* had a high similarity (80% - 90%). *Acacia mearnsii* and *Hibiscus diversifolius* showed a strong similarity (90%). *Tetradenia riparia* and *Vaccinium myrsinites* had 100% of similarity. The sub-group showed a high similarity with *Quercus lusitanica* (85%). Very high similarities were also found between *Ficus* spp., *Hypericum revolutum*, *Persea americana* and *Prunus africana* (100%). This sub-group is similar to *Grevillea robusta* (75%). Very high similarities were also found between *Cedrela serrulata*, *Senna spectabilis* and *Maesopsis eminii* (100%).

3.3. Growth and Spatial Distribution

3.3.1. Growth

Ficus thonningii is the largest tree that was found within this ecological rehabilitation scheme (max 280 cm). However, its growth stretches beyond the ecological rehabilitation period, having been planted by previous occupants who were later resettled. *Acacia melanoxylon* and *Maesopsis eminii* were large trees as well (163 - 175 cm). *Grevillea robusta* and *Pinus patula* reached a maximum of 130 - 180 cm. This is shown in **Figure 8**. The descriptive parameters of the growth of trees are presented in **Table 6**.

The tallest trees (**Figure 9**) were respectively *Maesopsis eminii*, *Cedrela serrulata*, and *Acacia melanoxylon* (35 - 45 m) followed by *Ficus thonningii*, *Eucalyptus* spp., *Persea Americana*, *Grevillea robusta*, *Cupressus lusitanica*, *Prunus africana*, *Podocarpus usambarensis*, *Pinus patula*, *Spathodea campanulata*, *Senna spectabilis* (15 - 30 m).

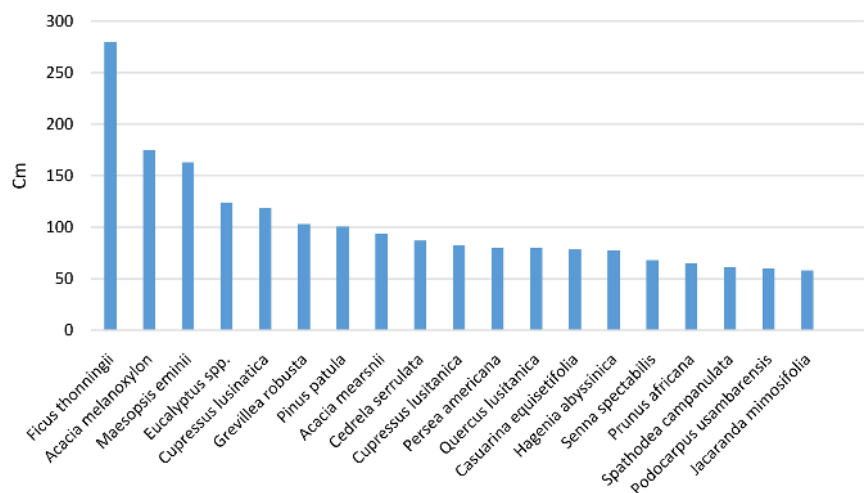
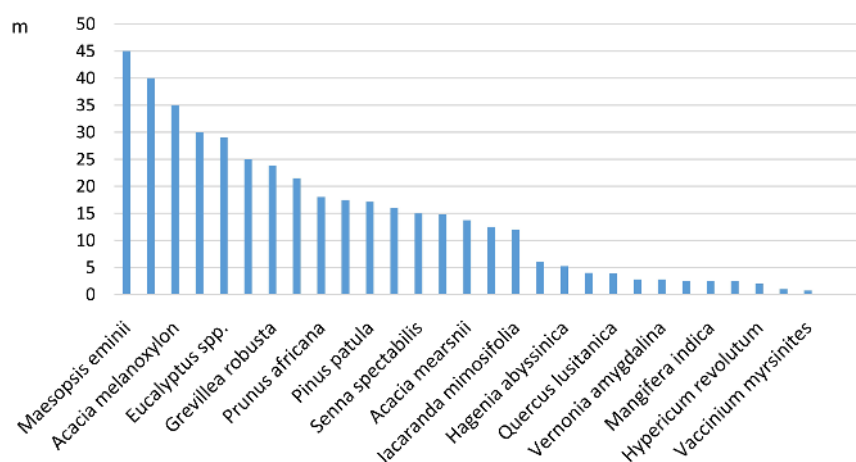


Figure 8. Average root collar diameter (cm).

Table 6. Descriptive parameters of tree growth within the ecological rehabilitated sites.

Scientific name	N	Mean	Median	SD	Minimum	Maximum
<i>Ficus thonningii</i>	1	280	280		280	280
<i>Acacia melanoxylon</i>	1	175	175		175	175
<i>Maesopsis eminii</i>	1	163	163		163	163
<i>Eucalyptus</i> spp.	6	124	117	67.47	30	200
<i>Cupressus lusitanica</i>	2	118.5	118.5	54.45	80	157
<i>Grevillea robusta</i>	6	103.2	100	23.58	79	130
<i>Pinus patula</i>	11	100.6	90	41.71	27	180
<i>Acacia mearnsii</i>	4	93.7	80	27.5	80	135
<i>Cedrela serrulata</i>	1	87	87		87	87
<i>Persea americana</i>	1	80	80		80	80
<i>Quercus lusitanica</i>	1	80	80		80	80
<i>Casuarina equisetifolia</i>	5	78.4	68	40.33	30	120
<i>Hagenia abyssinica</i>	2	77.5	77.5	45.96	45	110
<i>Senna spectabilis</i>	1	68	68		68	68
<i>Prunus africana</i>	1	65	65		65	65
<i>Spathodea campanulata</i>	1	61	61		61	61
<i>Podocarpus usambarensis</i>	2	60	60	28.28	40	80
<i>Jacaranda mimosifolia</i>	1	58	58		58	58

**Figure 9.** Average tree height (m) in the progressive ecological rehabilitation sites.

The descriptive parameters of the height of trees are presented in **Table 7**.

3.3.2. Spatial Distribution of the Growth Pattern

The trees were planted in 2012 on barren land. Five years later in 2016, the very dense vegetation already reached 10.8% and a two-fold increment in 2023 (22%). The moderately dense vegetation category was already very high in 2016 and similar in 2023 (24.1% - 25.9%). This is presented in **Figure 10**.

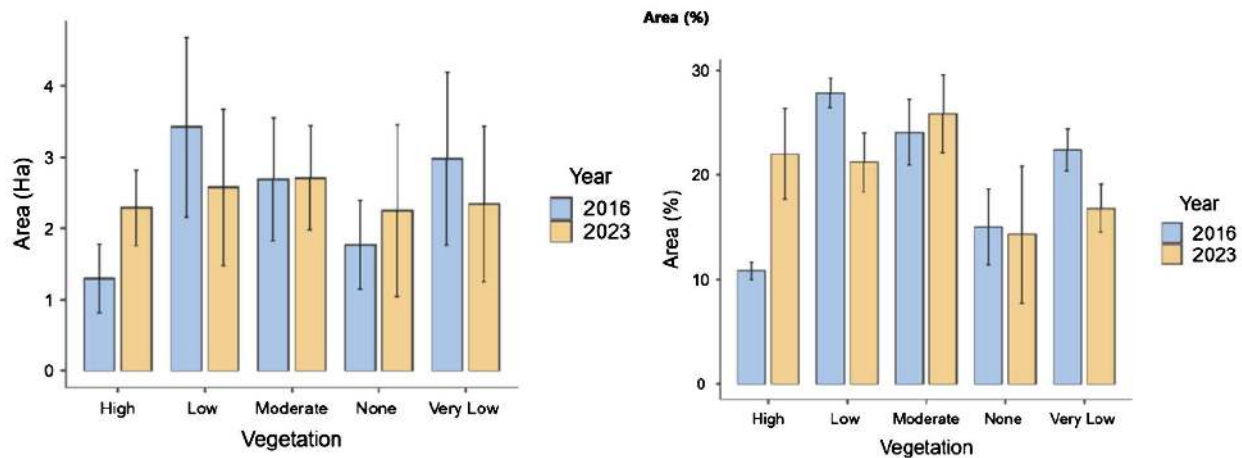


Figure 10. Vegetation growth between 2016 and 2023 (hectares and percentage).

Table 7. Descriptive parameters for tree height (m).

Scientific name	N	Mean	Median	Minimum	Maximum
<i>Maesopsis eminii</i>	1	45	45	45	45
<i>Cedrela serrulata</i>	1	40	40	40	40
<i>Acacia melanoxylon</i>	1	35	35	35	35
<i>Ficus thonningii</i>	1	30	30	30	30
<i>Eucalyptus</i> spp.	6	29	30	6	45
<i>Persea americana</i>	1	25	25	25	25
<i>Grevillea robusta</i>	6	24	26.5	12	35
<i>Cupressus lusitanica</i>	2	22	21.5	15	28
<i>Prunus africana</i>	1	18	18	18	18
<i>Podocarpus usambarensis</i>	2	18	17.5	10	25
<i>Pinus patula</i>	11	17	15	7.5	40
<i>Spathodea campanulata</i>	2	16	16	12	20
<i>Senna spectabilis</i>	1	15	15	15	15
<i>Casuarina equisetifolia</i>	5	15	15	4	25
<i>Acacia mearnsii</i>	4	14	10	10	25
<i>Jacaranda mimosifolia</i>	1	12	12	12	12
<i>Calliandra houstoniana</i>	1	6	6	6	6
<i>Hagenia abyssinica</i>	2	5	5.25	4.5	6
<i>Erica scoparia</i>	1	4	4	4	4
<i>Quercus lusitanica</i>	2	4	3.9	2.8	5
<i>Pulchea carolensis</i>	1	3	2.8	2.8	2.8
<i>Vernonia amygdalina</i>	1	3	2.8	2.8	2.8
<i>Cinchona ledgeriana</i>	1	3	2.5	2.5	2.5
<i>Mangifera indica</i>	1	3	2.5	2.5	2.5

Continued

<i>Sambucus canadensis</i>	1	3	2.5	2.5	2.5
<i>Hypericum revolutum</i>	1	2	2	2	2
<i>Erythrina abyssinica</i>	2	1	1	1	1
<i>Vaccinium myrsinites</i>	1	1	0.75	0.75	0.75
<i>Hibiscus diversifolius</i>	1	0	0.1	0.1	0.1

The barren land portion remained similar in 2016 and 2023, encompassing roads and infrastructures (15.1% - 14.3%). The Very Low to Low vegetation categories transformed into highly dense vegetation in 2023 as opposed to 2016 (Low: 27.9% - 21.2%, i.e. a 6.7% reduction; Very Low: 22.4% - 16.8%, i.e. a 5.6% reduction).

The descriptive parameters of the vegetation growth within the ecological rehabilitation sites are presented in **Table 8**.

Table 8. Descriptive parameters of vegetation growth within the ecological rehabilitation sites.

	Vegetation	Year	N	Mean	SE	Median	SD	Minimum	Maximum
Area (Ha)	High	2016	5	1.3	0.479	0.92	1.07	0.58	3.17
		2023	5	2.29	0.521	2.62	1.16	1.01	3.87
	Low	2016	5	3.43	1.256	2.02	2.81	1.52	8.18
		2023	5	2.58	1.09	1.7	2.44	1.14	6.92
	Moderate	2016	5	2.7	0.856	1.98	1.91	1.27	6.04
		2023	5	2.72	0.725	2.09	1.62	1.81	5.6
	None	2016	5	1.78	0.62	1.39	1.39	0.38	3.83
		2023	5	2.25	1.199	0.57	2.68	0.19	5.87
	Very Low	2016	5	2.99	1.207	1.49	2.7	0.84	7.34
		2023	5	2.35	1.08	1.2	2.42	0.67	6.41
Area (%)	High	2016	5	10.82	0.841	11.15	1.88	7.88	12.96
		2023	5	22.02	4.342	17.35	9.71	14.23	37.89
	Low	2016	5	27.86	1.42	28.45	3.17	24.13	31.54
		2023	5	21.22	2.831	21.92	6.33	11.26	27.62
	Moderate	2016	5	24.09	3.125	22.21	6.99	16.16	34.04
		2023	5	25.87	3.72	28.73	8.32	14.64	35.96
	None	2016	5	15.06	3.631	11.55	8.12	7.31	25.36
		2023	5	14.31	6.556	9.05	14.66	2.68	38.87
	Very Low	2016	5	22.41	2.007	23.65	4.49	16.15	26.99
		2023	5	16.83	2.311	18.08	5.17	10.56	23.57

The Normalized Difference Vegetation Index (NDVI) measured in 2016 and in 2023 at 5 ecological rehabilitation sites is presented in **Figure 11**.

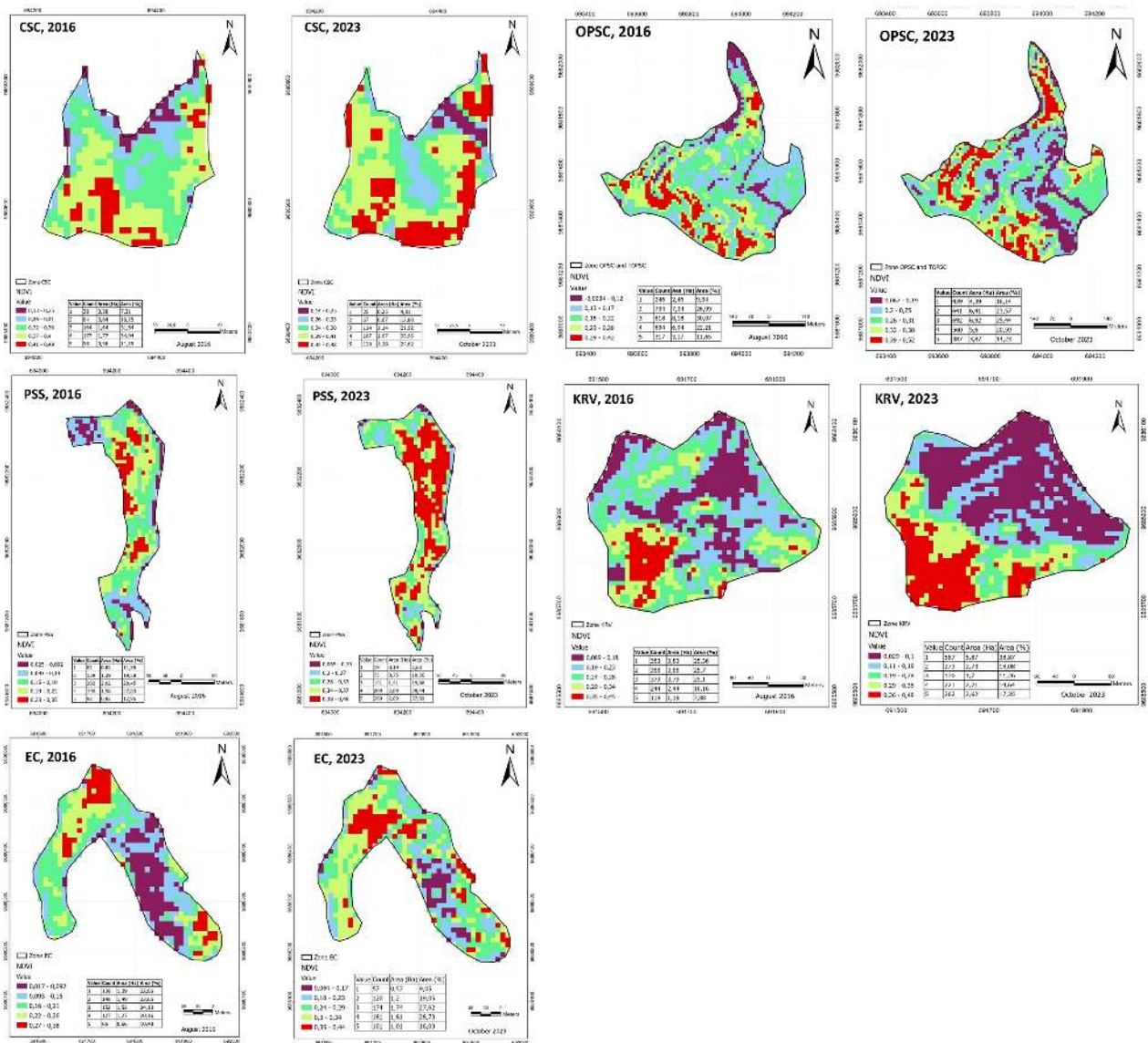


Figure 11. NDVI analysis of five ecological rehabilitation sites contrasting the years 2016 and 2023.

The effect of the progressive ecological rehabilitation is clearly highlighted on the 5 sites, showing good progress in vegetation cover and the success of the project. At the Plant site slopes (PSS) an increment in noted on dense vegetation from 12.96% - 87.19%. PSS was followed by the Exploration Camp (EC) whose dense vegetation increased from 10.48% - 72.38%. The Operators' Camp (OPSC) and the area above it (TOPSC) had its dense vegetation increasing from 11.65% - 60.26%, similar to the Camp Saio Cinjira (CSC) which had an increment from 11.5% - 60.58%. The Katuba resettlement village (KRV) had a lesser increment (7.88% - 17.35%), mainly due to the establishment of a resettlement village which is currently being grassed. **Figure 12** illustrates the Twangiza landscape before and after rehabilitation while **Figure 13** presents an ortho-rectified photo of some sites.

3.3.3. Local Species Regeneration

A number of species have been inventoried as barely seen on the ground prior to the progressive ecological rehabilitation and have regenerated thereafter at the sites. They are presented in **Table 9**.

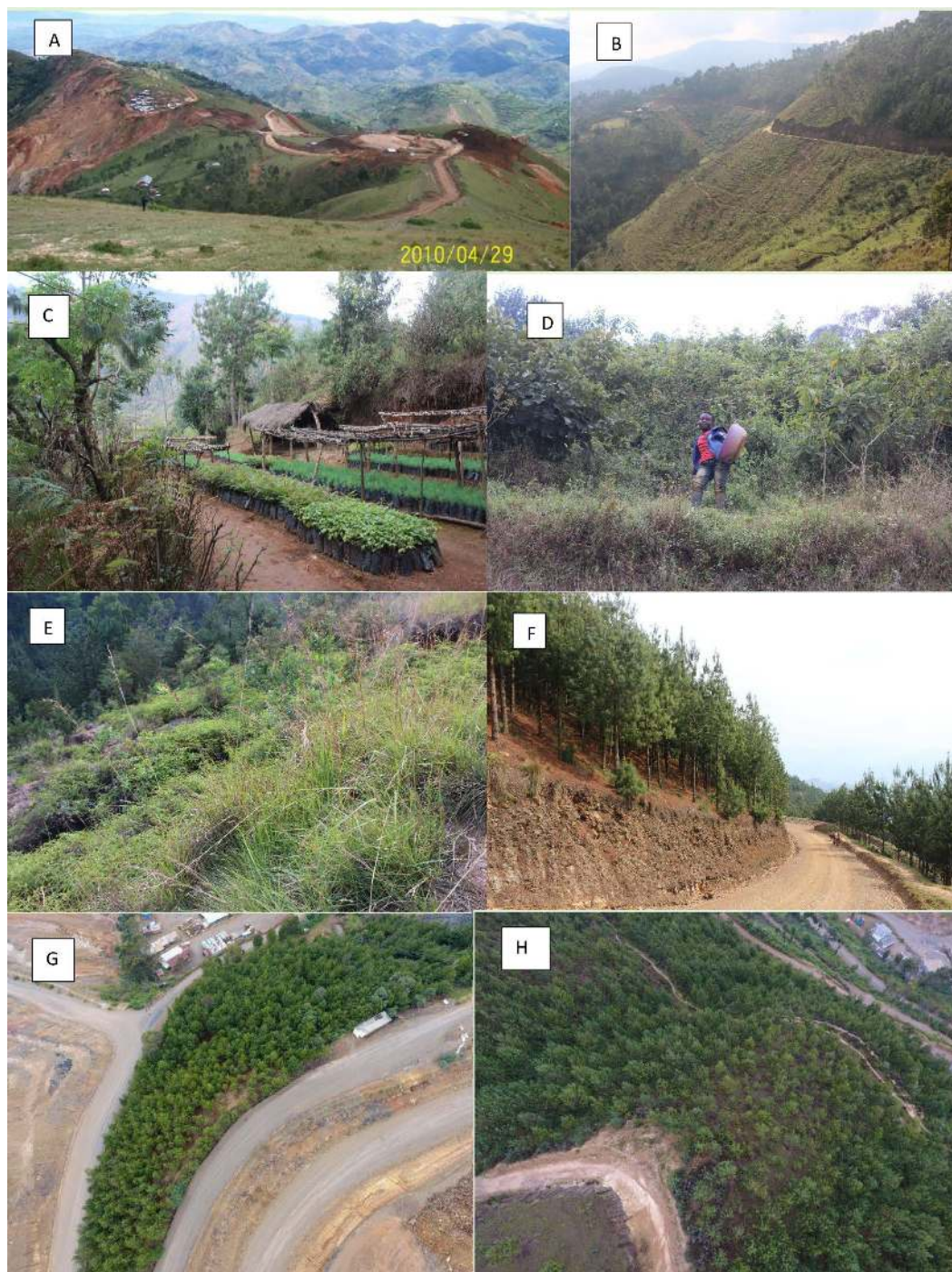


Figure 12. A: Plant site image before establishment; B: Buhamba access road with Eucalyptus trees; C: PSS tree nursery; D: OPSC with self-growing local species; E: local grass self-picking when undisturbed; F: *Pinus patula* planted on the sides of an access road; G: BGS with *Pinus patula* species; H: PSS with *Pinus patula* species.

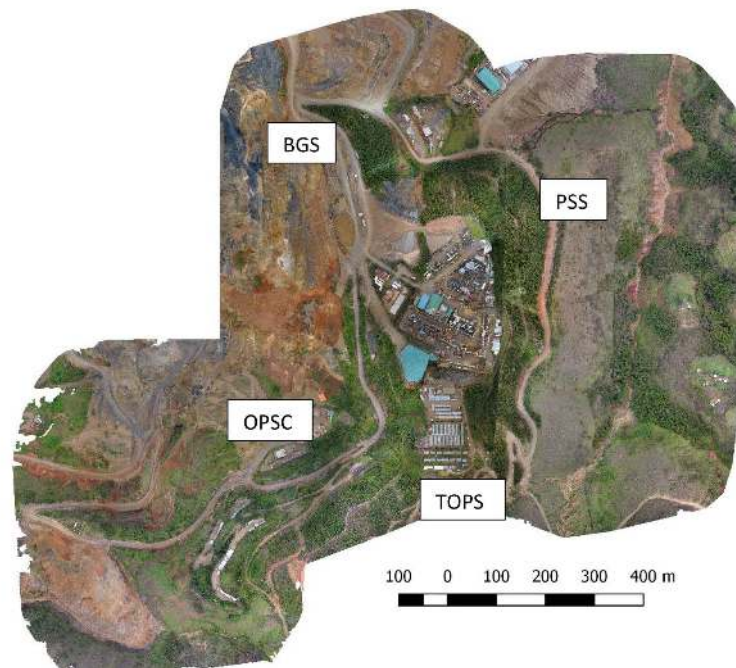


Figure 13. Ortho-rectified drone photo of the site showing four of the 9 afforested sites.

Table 9. List of species that have regenerated following the progressive ecological rehabilitation project.

Species	Site	Comments
<i>Acacia podalyriifolia</i>	EC	
<i>Myrianthus arboreus</i>	EC	Secondary forest species: 2 individuals found of which one with fruits [15 - 20 m high]
<i>Vaccinium stanleyi</i>	CSC; PSS	A species that had become scarce in the region but which is now common, growing under the shadow of planted trees
unidentified	BGS	Unknown species of 7 m high growing in between planted trees
<i>Solanum chenopodioides</i>	PSS	Vegetables that are eaten in high altitude areas such as Muhi, Cizuka and Bufulero. Locally called “Muhole”
<i>Clematis vitalba</i>	CSC	Found in the Cinjira ecological rehabilitation site and not seen before by the inhabitants
<i>Asparagus asparagoides</i>	CSC	

On the trees and shrubs side, the following species (local), planted during the rehabilitation process, have colonized the rehabilitation sites: *Calliandra houstoniana*, *Erica scoparia*, *Quercus lusitanica*, *Acacia mearnsii* (invasive), *Hagenia abyssinica*, *Prunus africana*, *Sambucus canadensis* and *Tetradenia riparia*.

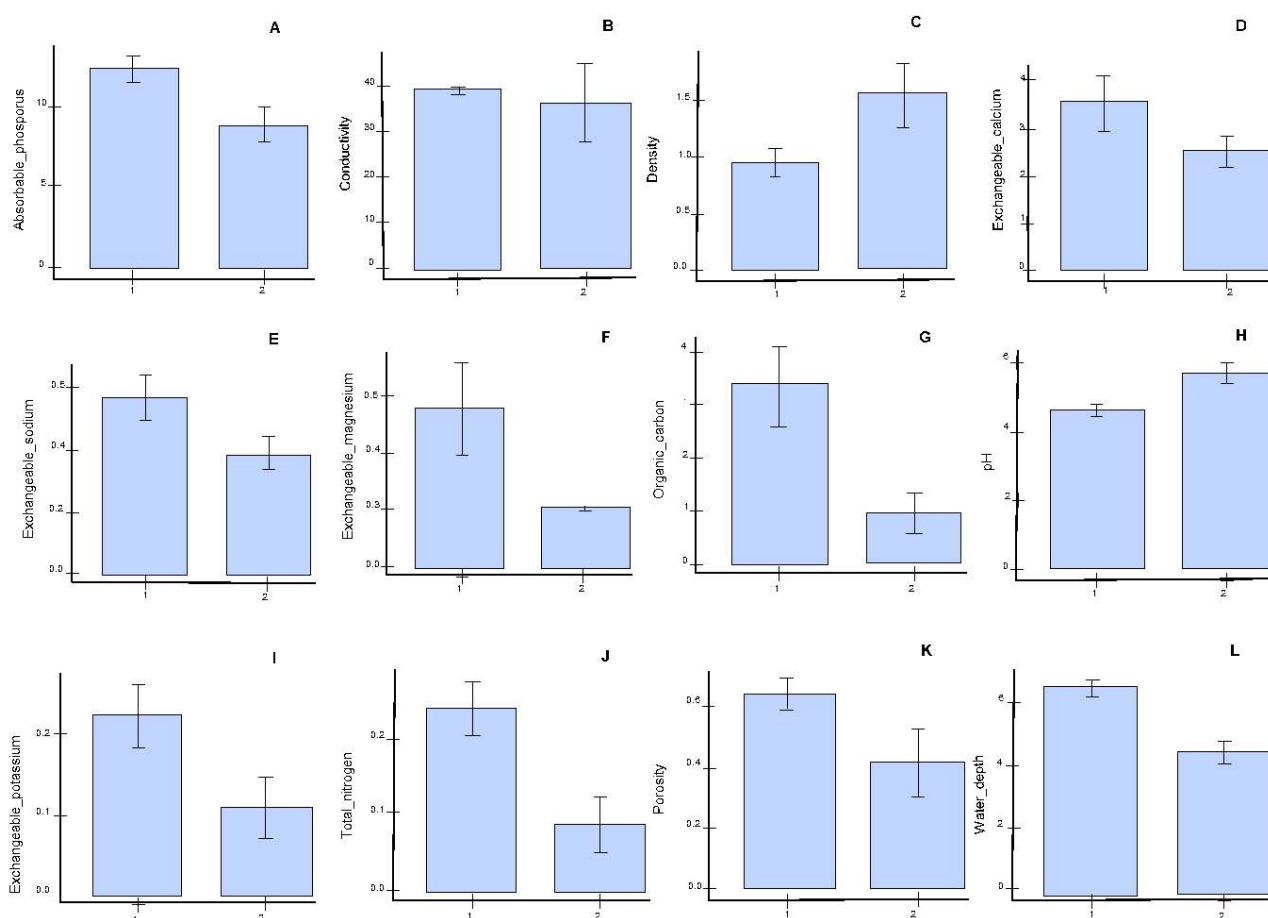
3.4. Assessment of Soil Improvement with Ecological Rehabilitation

The results show that ecological rehabilitation has considerably improved the soil,

both physically and chemically. The soil density has been reduced (61% as compared to non-rehabilitated sites) to the advantage of porosity (1.57 times increment). Water depth has increased 2m more on average ($P = 0.01$). Conductivity has been stabilized as opposed to strong fluctuations before the rehabilitation. This is shown in **Figure 14**.

Organic carbon has been boosted 3.5 times ($P = 0.05$) having risen from very low to moderate and high levels, like total nitrogen (2.67 times increment; $P = 0.03$) from moderate to very high levels and exchangeable magnesium (2.71 times; $P = 0.01$) having risen from low to moderate levels, and absorbable potassium (2.1 times) which increased from very low to moderate levels. Absorbable phosphorus shows an increment of 39%, though its levels are still low; unlike exchangeable sodium which rose from low to moderate levels (46%) and calcium (41%) which has risen from very low to low levels. The clustering of the progressive ecological rehabilitation sites according to their physical and chemical soil properties is shown in **Figure 15**.

The non-rehabilitated sites are clearly clustered for worse physical and chemical parameters altogether; i.e. URSa, KRV_US, URS2a; the Bonded Laydown yard



A) Absorbable phosphorus; B) conductivity; C) density; D) exchangeable calcium; E) exchangeable sodium; F) exchangeable magnesium; G) organic carbon; H) pH; I) exchangeable potassium; J) total nitrogen; K) porosity; L) water depth.

Figure 14. Soil physical and chemical properties at the progressive ecological rehabilitation sites.

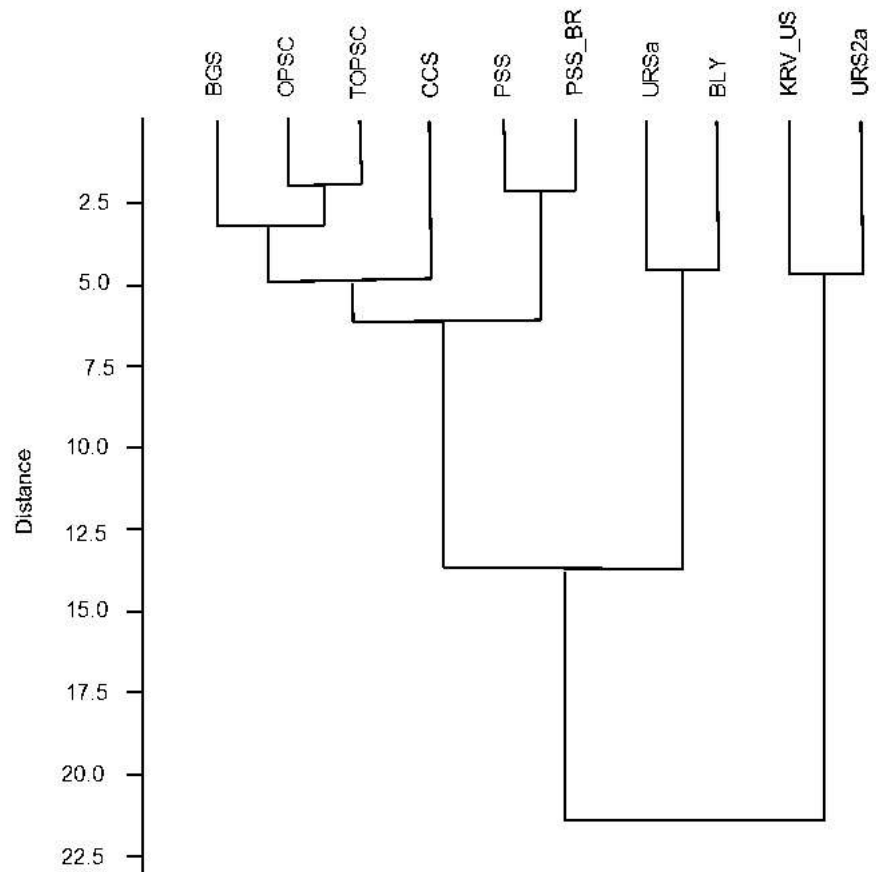


Figure 15. Clustering of the sites according soil parameters altogether (Euclidian distance).

(BLY) which shows up in that group has been rehabilitated but was not subject of disturbance during the mine construction. This may be the reason why its soils kept the similar properties.

The effects of ecological rehabilitation on the pH of soils are not obvious as shown in **Figure 16**. This situation may require more investigations because the soils at the sites are usually quite acid with an influence of altitude to some extent.

3.5. Community Uses and Threats to the Restored Ecosystems

Grazing by domestic cattle was observed as the main ecosystem service in the progressive ecological rehabilitation sites (66%) as shown in **Figure 17**. Most cattle are composed of cows (*Bos taurus*), goats (*Capra hircus*) and sheep (*Ovis aries*) which graze on grass that was planted for erosion control and soil cover as part of the rehabilitation exercise from the vicinities. Most plots have been subject to illegal bush fires (88%), mainly in quest of fresh grass for grazing, an unfortunate habit that has taken place which has negative effects on the vegetation growth rate and success of the rehabilitation project.

Provision of fire wood accounts for 8% among the ecosystem services. Women

and children are wandering in quest of firewood as they do not have any other source of energy, and barely no trees planted at their homes. This activity increases when the project embarks on regular tree pruning which is beneficial for rapid tree growth. Local farmers also use pruned sticks as supports for volubile beans (*Phaseolus vulgaris*). Grass, especially *Muhlebergia capillaris* and *Brachypodium retusum*, is used as roof construction and floor cover inside thatch houses, where they act as temperature control. They are very effective for erosion control and as land cover. Some of the plants are used for medicinal purposes but have not been further investigated.

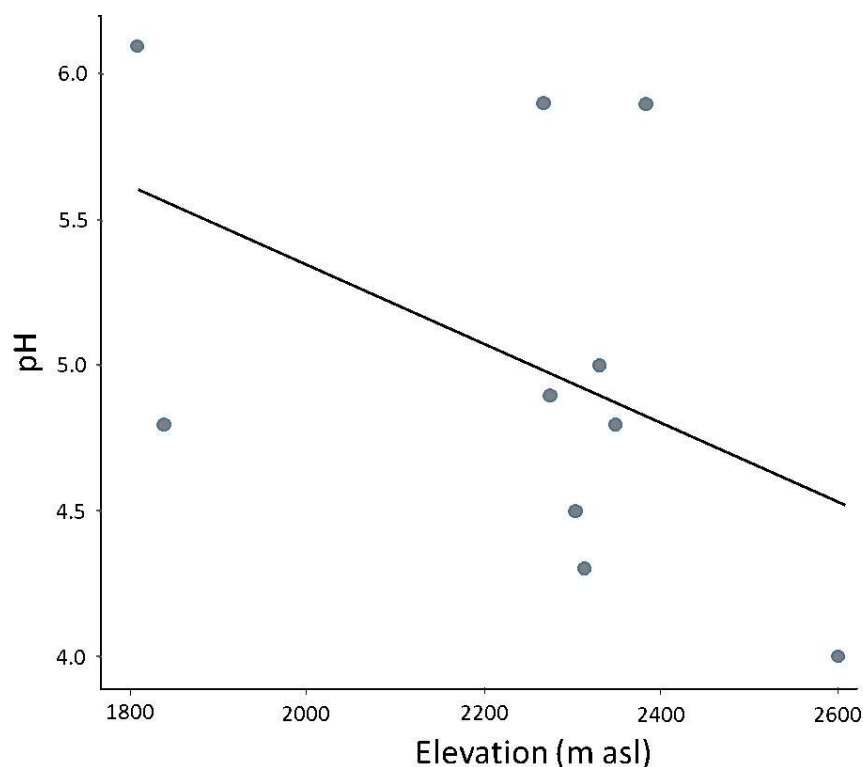


Figure 16. The relationship between elevation and the soil pH.

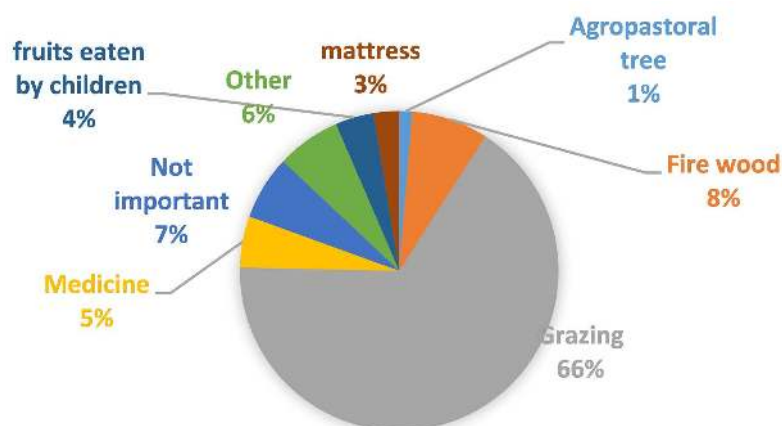


Figure 17. Community uses of the vegetation at the progressive ecological rehabilitation sites.

The main uses of the community of the vegetation present in the progressive rehabilitation sites are presented in **Table 10**.

Table 10. Observed uses of vegetation at the progressive ecological rehabilitation sites.

Usage	Family	Type
Medicinal		
<i>Vernonia amygdalina</i>	Asteraceae	Shrub
<i>Thelypteris dentata</i>	Aspleniaceae	Herbaceous plants
<i>Indigofera erecta</i>	Fabaceae	Herbaceous plants
<i>Pycnostachys erici-rosenii</i>	Lamiaceae	Herbaceous plants
Grazing, Roofing, Erosion control, Ground cover		
<i>Brachypodium retusum</i>	Poaceae	Herbaceous plants
<i>Cynodon dactylon</i>	Poaceae	Herbaceous plants
<i>Muhlenbergia capillaris</i>	Poaceae	Herbaceous plants
Fruit		
<i>Vaccinium myrsinites</i>	Ericaceae	Herbaceous plants
Fire wood		
<i>Pinus patula</i>	Pinaceae	Tree
<i>Quercus tomentella</i>	Fagaceae	Shrub
<i>Erica scoparia</i>	Ericaceae	Shrub
<i>Grevillea robusta</i>	Proteaceae	Tree
Mattress/Bedding		
<i>Lycopodium clavatum</i>	Lycopodiaceae	Herbaceous plants

Among the grasses *Brachypodium retusum*, *Muhlenbergia capillaris*, *Cynodon dactylon* are the most used by communities for grazing, roof construction, erosion control and ground cover to mitigate dust and mud. *Vernonia amygdalina*, *Thelypteris dentata*, *Indigofera erecta*, *Pycnostachys erici-rosenii* are frequently used for medicinal purposes. Among the trees, *Pinus patula*, *Quercus tomentella*, *Erica scoparia*, and *Grevillea robusta* provided were mostly used as firewood.

Lycopodium clavatum is often utilized by community who collect it from nature and put it in sacs to be used as mattresses that they lay on the ground. *Muhlenbergia capillaris*, *Brachypodium retusum*, *Cynodon dactylon* and *Buddleja globosa* were deliberately chosen for grassing of berms, slopes and selected areas for their importance in erosion control.

3.6. Fungi

The following fungi species were found in the progressive rehabilitated sites, especially at PSS and BGS. *Amanita muscaria* was most encountered, followed by *Suillus* spp., *Lacaria* spp., *Panaeolus* spp. and *Coprinus* spp. They are shown in **Figure 18**.

From top-left to top-right: *Amanita muscaria*; *Suillus* spp. and from bottom left to bottom right: *Laccaria* spp., *Panaeolus* spp. and *Coprinus* spp.



Figure 18. Fungi species encountered in the progressive rehabilitation sites.

4. Discussion

4.1. Revisiting the Planned Objectives

Achieving the revegetation of degraded areas should be the most important rehabilitation goal. The aim should be to progressively rehabilitate an area and not wait until the closure of the mine (Schmidt, 2002). Rehabilitation is very costly. It is therefore very important that the efforts put into rehabilitation projects yield successful outcomes (Australian Government, 2016).

Here, it is essential to evaluate whether the ecological restoration objectives have been reached at Twangiza.

The most successful sites were PSS, OPSC, TOPSC, EC, and BLY. They are more successful because they are more closely monitored. This can also be seen in the vegetation cover and growth. Being close to the process plant, within the Exploration Camp and by the Bonded Laydown Yard, there was constant movement of staff and security services, which discouraged intruders. Herbaceous plants are mainly used to fix the soil, combat surface water and wind erosion, and reduce sedimentation in surface water drains. In fact, most of the objectives were well achieved, except the tree planting on the Kadubo-Cinjira road section. These were either taken away, destroyed, or damaged on a frequent basis by bypassers. The community sensitization exercise may be considered at 65% - 70%, as we still have a lot of people not yet convinced, adhering to what they are told, and/or manipulated by those who are looking for the failure of the project.

The strengths are the cover of the sites, the reduction of erosion, the windbreak, the improvement of the landscape, etc. The weaknesses are rather the risk of bush-

fire lit by ill-intentioned people, the attraction of villagers in search of pasture and firewood, and the facilitation of theft and incursions.

Increased surveillance and more staff are needed to raise awareness so that everyone is aware of the ecological and social benefits. But this comes at a cost that not everyone, especially management, easily understands. Many more species have grown, and more rapidly, at lower altitudes (1900 m) than at higher altitudes (2200 m and above). That is what is obvious. *Pinus patula*, *Grevillea robusta*, and *Hagenia abyssinica* stood out for their strong growth at altitude. *Hagenia abyssinica* is known to be an altitude and local species.

Our recent results on the surface and groundwater quality (Basima et al., 2025b), microclimate indicators and air dust dynamics (Basima et al., 2025c), and animal recolonization (Basima et al., 2025a) further show that some of the major expected benefits of mine reclamation, namely landscape restoration, water quality improvement, wildlife habitat rehabilitation, water and soil conservation, dust and air pollution control, carbon storage, and economic benefits, have been granted to some extent on the afforested 100 hectares rehabilitated within the core sites and at least 757 ha within the general communities in the mine vicinities. Of course, this is still a small geographic extent, as compared to the area candidate for ecological rehabilitation after mine closure. Landscape restoration is granted in the afforested area. In this way, reclamation reduced the visual impact of inactive mines and restored the natural aesthetics of the area.

4.2. Environmental Impacts

4.2.1. Water

Basima et al. (2025b) evaluated the water quality improvement in the aftermath of the ecological rehabilitation, besides the crucial role of the Tailings Management Facility (TMF). A decade-long environmental monitoring, with samples shipped to an accredited lab in South Africa brought up results that show non-significant changes in natural waters, within the accepted standards, regarding quality and quantity. This includes rivers, boreholes and springs; upstream, within mine site and downstream. The results indicate that TDS, EC were higher in the mine site. pH results indicate that most of the stations were found within the acceptable limits as far as the DRC, and IFC effluent discharge guidelines are concerned, which range between 6 and 9. A TDS level of less than 600 mg/liter is generally tolerated. The water quality was also confirmed by the benthic macroinvertebrate bio-indicators. In contrast, during the baseline study, Fe was found everywhere with elevated values almost throughout the river system. Elevated arsenic was found in the upper reaches of the Mwana River, Upstream, at the alluvial area on the Mwana River. Elevated Mn, Ni and Pb were detected in the Mwana and Lulimbohwe Rivers, downstream of the mine (Morgan et al., 2009). The groundwater flow remained consistent, indicating that the nearby Itombwe montane forest reserve is stabilizing the zone, in addition to the positive impact of the progressive rehabilitation project as well as its related community-based induced afforestation program that facilitates the surface water retention, gradual and regu-

lar infiltration reaching the water table at a regular basis. In fact, mine reclamation processes often involve the construction and maintenance of sustainable drainage systems. This helps reduce water pollution by controlling surface water flow and minimizing soil erosion and sediment runoff into rivers and lakes. Additionally, reclamation may include improving water quality in former mining ponds to support aquatic life.

In contrast, during the baseline study, [Bytebier et al. \(2008\)](#) encountered generally disturbed and secondary vegetation types at Twangiza. By then, an estimated 90% of the land had been transformed by anthropogenic activities. Regarding Wildlife Habitat Rehabilitation, the avifauna was depauperate, both in number of species and their abundance before the ecological rehabilitation. By then, no mammals or reptiles were recorded within the footprint area. But recently, [Basima et al. \(2025a\)](#) found a total of 22 insect genera, 4 amphibian species, 11 reptile species, 43 bird species and 11 small mammal species. All of them were strongly settled in the core area within the afforested sites. Those results clearly demonstrate the positive impact of the afforestation on insect, amphibian, reptile, bird and small mammal's diversity in this area. From a zoological point of view, the little remaining biodiversity was of little importance and required no special attention. In fact, [Bello et al. \(2024\)](#) summarized the impacts of animals. Animals pollinate approximately 90% of flowering plant species, disperse seeds of up to 70% of woody plants, and structure microbial symbiotic communities that promote nutrient acquisition in >90% of plants. As such, animals influence key limiting steps essential for the arrival and establishment of native vegetation. [Jones \(2016\)](#) opined that, traditionally, ecological restoration is based on re-establishing patterns of vegetation communities with the expectation that wildlife will recolonize, restoring the ecological function. However, in many restoration projects, wildlife fails to recolonize, even when vegetation is restored, in many cases because revegetated habitats lack the critical features required by wildlife. It was assumed that the proximity of the Itombwe forest grants good animal recolonization Twangiza. Additionally, [Sucofindo \(2023\)](#) indicates that plants planted as part of mine reclamation can play a role in storing carbon dioxide (CO₂) from the atmosphere, helping mitigate the impact of climate change. Trees and other plants absorb CO₂ during photosynthesis, contributing to balancing human-induced CO₂ emissions. Evidences of microclimates were highlighted by [Basima et al \(2005c\)](#).

With the development and maintenance of ecological restoration sites, more surface water is believed to be captured by these ecosystems, allowing more water retention and gradual release for both surface and groundwater. Debate on water supply. This, in turn, facilitates the growth of native species. The depth of the water table ranges from around 90 m on the summit of the ridge to about a meter to the Mwana River valley (alluvium). A few artesian (free outflow of water) boreholes, intersecting the fractured aquifer, are found on the limbs of the Twangiza anticline.

The impact of ecological restoration on water supply, river recharge and groundwater is a puzzle. [Ouyang et al. \(2021\)](#) stated that, although afforestation

has been recognized as conserving water resources, improving water quality and mitigating river flood, the role it plays with groundwater resources is not fully investigated. Simulations showed that the average groundwater level had declined 1.2 m in the croplands over a 20-year period from 1987 to 2007, whereas the average groundwater level had declined only 0.13 m after afforestation for the same simulation period and occurred mainly due to no groundwater pumping and a slight increase in groundwater recharge. Our study implies that afforestation on low-productive croplands in a humid subtropical region could be an alternative to mitigate groundwater depletion.

Zhang & Lu (2018) acknowledged that afforestation is the preferred measure for policymakers to solve a range of ecological problems, as it is generally believed that forests help to improve soil health and quality, reverse land degradation, halt land desertification, and provide clean water through an intensified water cycle. For example, more than 2 square kilometers of forest expansion can increase the possibility of rainfall. Trees transport water to the air, and water vapor moves to another place which can be geographically far from the afforested location. Evidence shows, for example, that water supply may start to improve after 30 years in the case of pines and 15 years in the case of eucalyptus. But Mourot et al. (2021) noted stream flow reductions following increased forest cover and water balance calculations, suggesting a reduction of the base flow that may be a consequence of tree water uptake. Silveira et al. (2016) observed that the specific discharge decline is particularly high for drier autumns and winters (32% to 28%) when the corresponding rainfall varies from 275 to 400 mm.

Lu et al. (2018) proved that afforestation in arid and semiarid northern China will exacerbate the groundwater decline while creating enormous opportunity costs. Thus, the afforestation program must be urgently reassessed and the water-use efficiency of vegetation must be considered when planning future ecological restoration both to make the restoration more cost-effective and to protect the ecosphere. The potential groundwater table decline from 1952-2011 ranged from 21.5 m in Shaanxi Province to 40.0 m in a neighboring province. Farley et al. (2005) found that the annual runoff was reduced on average by 44% and 31% when grasslands and shrublands were afforested, respectively. Eucalyptus had a larger impact than other tree species in afforested grasslands 75%, compared with a 40% average decrease with pines. Runoff losses increased significantly with plantation age for at least 20 years after planting. For grasslands, absolute reductions in annual runoff were greatest at wetter sites. In a region where natural runoff is less than 10% of MAP, afforestation should result in a complete loss of runoff; where natural runoff is 30% of precipitation, it will likely be cut by half or more when trees are planted.

However, on the positive side, in regions like Twangiza, less mine-induced pollution will occur when runoff decreases.

4.2.2. Soil Amelioration

Our results show that ecological rehabilitation has considerably improved the soil,

both physically and chemically. The soil density has been reduced to the advantage of porosity. Water depth has increased 2 m more on average. Conductivity has been stabilized. Organic carbon has been boosted 3.5 times, like total nitrogen and exchangeable magnesium, and absorbable potassium and absorbable phosphorus, and exchangeable sodium and calcium. But the effects of the ecological rehabilitation on the pH of soils are not obvious, because the soils at the sites are usually quite acidic with an influence of altitude to some extent.

Bandyopadhyay and Maiti (2019) opined that available phosphorus, exchangeable magnesium, organic carbon, clay content, field moisture, available nitrogen, electrical conductivity, and pH are identified as the most influential parameters that regulate the health of reclaimed mine soil. Exchangeable calcium, magnesium, cation exchange capacity, sand, silt, clay content, field moisture, available phosphorus, and pH are the controlling properties for forest soil. Neuenkamp et al. (2024) emphasized that soils are the backbone of terrestrial ecosystems, underpinning their biodiversity and functioning. They are also key to agricultural production and ecosystem development. Organic matter content may again serve as a good proxy of both soil biodiversity and functioning, as it promotes soil quality and biodiversity. Vegetation cover and vegetation diversity, both in time and space, might serve as a good indicator of the interdependence of vegetation and soil. Yang et al. (2014) indicated that soil organic matter (SOM) is the most important component of soil fertility. And SOM is often used to assess the soil amelioration. Soil nutrients have a close relationship with the soil organic matter. In this multivariate complex, we find it necessary to find proxies for soil quality evaluation, i.e., the soil organic matter content.

On their turn, Guo et al. (2025) demonstrated that plant species had a significant effect on soil, plant, and microbial characteristics. Le Roux (2002) noted the multidimensional requirements and impacts of ecological restoration of mines. It implies managing the terrain to limit erosion and soil compaction, rapidly making use of the biological potential of available topsoil, remedying nutrient deficiencies (by adding soil improvement material and fertilizer and planting nitrogen-fixing and mycorrhiza-bearing species), reducing toxic metal concentrations, creating a microclimate that promotes germination, and selecting appropriate species. The selection should be made among pioneer and native species and should also consider species associations and successions over the longer term. Whatever the site under consideration, the use of nitrogen-fixing species is always beneficial and even essential to successful rehabilitation. In this regard, the most prevailing species among nitrogen-fixing ones here are *Acacia mearnsii*, *Calliandra calothyrsus*, *Casuarina equisetifolia*, *Chamaecrista fasciculata*, and *Erythrina abyssinica*.

4.2.3. Air Quality, Dust and Heavy Metals

The results showed that when operational, the mine produced 7 to 10 times more dust than when not operational, which is attributed to mobile and mineral-extracting equipment. Momoh et al. (2013) observed that suspended particulate matter in the air ranged from 60.25 to 1820.45 $\mu\text{g}\cdot\text{m}^{-3}$ at the Mukula mine in Lim-

popo, South Africa. Average values revolved around $420.7 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ at Twangiza, though apart from pragmatic knowledge, no evidence was given here about the effects of the afforestation as a windbreaker on dust propagations.

For the purpose of dust retention, [Chen \(2018\)](#) discussed the imperative of selecting appropriate exotic plant species for heavy metal removal. [Sheng et al. \(2024\)](#) recommended prioritizing the utilization of plants with robust dust-retention abilities and implementing a mixed planting approach encompassing a combination of trees, shrubs, and herbaceous plants. [Jia et al. \(2021\)](#) identified some plant species that accumulate the highest amounts of Cu, Zn, Cr, and Pb. Plant leaves can simultaneously capture dust and its bound toxic metals. [Bridhikitti et al. \(2024\)](#) found that maximum dust-capturing capacities for the forest trees ranged from 0.95 to $5.197 \text{ g}\cdot\text{m}^{-2}$. Leaf dust capturing capacity was enhanced under cold and dry weather, strong winds, and for trees with defoliated or irregular shapes. The study in the Ryukoku forest (dominated by conifer and deciduous trees) in Japan reported that the forest could purify the polluted air via the deposition of air pollutants, NO_2 and O_3 , onto leaf surfaces. Also, the effect of tree windbreak results in lower air pollutant concentration inside the forest compared to the outside level ([Ichikawa et al. 2015](#)). [Erkebaev et al. \(2021\)](#) estimated that one hectare of green plant species cleans about 18 million m^3 of air per year.

4.2.4. A Tool for Environmental Education and Law Improvement

The ecological progressive rehabilitation can be used as a tool to help:

- 1) Educate students from primary, secondary, and tertiary levels to grasp the basics, get hands-on experience on how tree nurseries are selected, positioned with regards to solar illumination and photosynthesis action, and prepared. This can enable them to replicate the exercise and enjoy tree planting;
- 2) Through various educational and sensitization visits, students and the general community may develop affinities with the environment by witnessing the role of trees in the environment, especially with regard to erosion control, farm fertilization, ecosystem and community services like firewood provision, and landscape scenery;
- 3) To discourage and educate communities on the negative effects of bushfires on the long-term fertility of soils and their nutrient quality;
- 4) Promote ecotourism by encouraging local organizations or associations to get involved;
- 5) Adapt the mining law in the DRC, considering the many benefits related to skills and experience acquisition on species identification, suitability, and soil improvement over time—way before mine closure.

4.3. Ecosystem Services

[Morrison-Saunders \(2019\)](#) stated that the broad rehabilitation goal currently approved by regulators focuses on biodiversity targets, does not explicitly capture a community perspective, and is proving hard to deliver, notwithstanding that community members have also been employed by the mining company to work on

progressive rehabilitation of the first pit area, which will have a 5500 ha final footprint of mining.

Gao et al. (2024) indicated that the indirect value generated by ecological restoration is found to be 3.13 times the direct value, emphasizing the importance of including these indirect benefits in project evaluations. This indicates that direct economic benefits alone do not fully compensate for project inputs, underscoring the necessity of assessing ecological restoration projects beyond economic metrics.

Economic benefits have not been genuinely evaluated in the current study. It is true that some jobs have been created. The project hired 8 staff members from the environment department and 35 women and 5 men from the community. Additionally, 20 community liaison members were involved. In total, 70 jobs were directly linked with progressive ecological rehabilitation. Reclaimed land can be used for other economic purposes, such as agriculture, forestry, or tourism. In this case, we have just evaluated the community uses of the afforested sites. Grazing by domestic cattle (cows, goats, and sheep) is the predominant community use. In this context where genuine pastures are scarce, animals graze on grass that was planted for erosion control and soil cover as part of the rehabilitation exercise from the vicinities. Another rare commodity is firewood. Women and children wander in quest of firewood as they do not have any other source of energy and barely any trees planted at their homes. This activity increases when the project embarks on regular tree pruning, which is beneficial for rapid tree growth. Local farmers also use pruned sticks as supports for volubile beans, which boosts production. Herbaceous plants, especially *Muhlenbergia capillaris* and *Brachypodium retusum*, are used as roof construction and floor cover inside thatch houses, where they also act as temperature control. Some of the plants are used for medicinal purposes but have not been further investigated.

4.4. Exotic Plants vs Natives

The predominant exotics here are *Pinus patula*, *Grevillea robusta* and *Podocarpus usambarensis*. Native species include *Hagenia abyssinica* and *Prunus africana*. People from the surrounding community come into the woodlands and cut them down, claiming that they grow naturally, as if it is a valid justification for their inappropriate action. In the studied areas, which are seven years old, the projective cover is 80% - 90% and is close to the projective cover in undisturbed areas (95%). With an increase in the age of reclamation, an increase in species diversity is noted up to 18 species (in which a high proportion of native species is in intensive processes of restoration of disturbed fertile rocks and/or FSL (fertile soil layer), provided that this indicator fluctuates in different periods of time, as a result of the gradual replacement of annual plant species by perennial ruderal species and their simultaneous replacement with native species. Very little is known about the long term success of native vegetation establishment on mined lands and the ability of rehabilitated vegetation to cope with future disturbances and therefore work

needs to be conducted on the decommissioning of mine-sites in arid pastoral regions and on their resilience to grazing.

We found that native species are more interesting. But with all the stress that the region has undergone, through deforestation, the search for agriculture fields, pastures and bush fires, it is difficult to lean towards them alone. Their spores are hidden. With ecological rehabilitation, these species are emerging in the shadow of exotic species. This is a good thing, because many of them are said by the local population to have medicinal properties. However, every time when the indigenous species grow up in the rehabilitation scheme, the local community lashes them out for use, claiming that they have grown naturally and that the mining company has nothing to say about their growth. It will take a long time before individual attitudes change to protect the native plants. It should also be said that in our experience native species grow very slowly compared with exotic species.

But [Zhang et al. \(2024\)](#) stated that there is an ongoing debate among ecologists on the value of exotic vegetation to ecosystem resilience and integrity, with authors arguing that in order for ecosystems to survive in future climates, exotic species with similar conditions in their current range must be considered. Others deem biodiversity vital for ecosystem functions and services, stating that most biodiversity losses are man-induced and should be addressed through the enhancement of native communities. Natives not only present high adaptive capacity, but also provide additional benefits for biodiversity, ecosystem integrity, and for people. In a broader framework, the literature demonstrates a preference for the use of native species in most situations. In compliance with the latter opinion, [Bailly et al. \(2021\)](#) reported that in New-Caledonia that soil constraints limited the use of exotics, suffering from substrate toxicity and low fertility, while the natives, mostly endemics sustainably thrived.

In this vein, [Morandin and Kremen \(2013\)](#) found that at mature hedgerow sites, wild bee abundance, richness, and diversity were greater on native plants than exotic plants. At new sites, where native plants were small and had limited floral display, the abundance of bees was greater on native plants than exotic plants. [Tognetti et al. \(2010\)](#) argued that exotic plants are major constituents of species pools in modern landscapes and while meeting conservation goals, the removal of exotic plants may be required along with native grass seeding. [Mazzolari et al. \(2011\)](#) even reminded that managers of many reserves estimate they spend an enormous amount of their annual operating budget on the control of non-indigenous species.

In contrast, [Meiners \(2007\)](#) found that exotic species behave in essentially the same way as native taxa within dynamic communities, suggesting that abundant native and exotic plant species are exploiting the same range of ecological strategies resulting in similar roles within communities. [Daehler \(2003\)](#) postulated there appear to be few “super invaders” that have universal performance advantages over co-occurring natives; rather, increased resource availability and altered disturbance regimes associated with human activities often differentially in-

crease the performance of invaders over that of natives.

4.5. Spatial Variation, Diversity and Animal Recolonization

The objectives that worked best were those that fitted in with the sites around the plant, thanks to good monitoring. Being close to the process plant and other important facilities, there was constant movement of staff and security services, which discouraged intruders. So, the most successful sites were PSS, OPSC, TOPSC, EC and BLY. They are more successful because they were more closely monitored. This can also be seen in the vegetation cover and growth. The Cinjira and Kadubo road sites did not work well due to multiple sabotages by the local community, who did not understand the objectives of the project, but also by ill-intentioned people seeking to demonstrate at all costs that Twangiza Mining had done nothing in the community. Xiang et al. (2004) found that areas that were not performing well, were typically impacted by grazing activities. Beche et al. (2022) observed that human disturbances, such as coffee management and grazing declined with distance to forest edges, and penetrated at least a kilometer into the forest. Slope was not related to disturbance levels, but several types of disturbances were less common at higher elevations. Many more species have grown, and more rapidly, at lower altitudes (1900 m) than at higher altitudes (2200 m and above), which is obvious. *Pinus patula*, *Grevillea robusta* and *Hagenia abyssinica* stood out for their strong growth at altitude. *Hagenia abyssinica* is known as an altitude species.

Haagner (2018) found positive correlations between rehabilitation site age and landscape function indices, suggesting that some aspects of ecosystem development were occurring over time. In some sites, deterioration in the substrate quality as a growth medium was observed with increases in acidity and salinity. This was most likely caused by pyrite oxidation in the tailings and the high concentrations of free salts. The increasing acidity and salinity resulted in vegetation senescence and declines in landscape function.

König et al. (2022) found that recovery of forest structure was closely associated with interactions between soil quality and the planted tree communities, and that tree diversity recovery was positively associated with the amount of surrounding forests. We also observed that forest structure and diversity recover more slowly in mine tailings compared to pit surroundings.

4.6. Species Dominance and Plant Cover

Cristescu et al. (2012) showed that species densities and richness were frequently lower in rehabilitated compared to undisturbed areas, even more so when only native species were considered. Soloviev et al. (2021) found projective covers of 80% - 90% at seven-year-old sites, which was close to the projective cover in undisturbed areas (95%). With an increase in the age of reclamation, an increase in species diversity was noted up to 18 species (in which a high proportion of native species is of intensive processes of restoration of disturbed fertile rocks) and/or FSL (fertile soil layer), provided that this indicator fluctuates in different periods

of time, as a result of the gradual replacement of annual plant species by perennial ruderal species and their simultaneous replacement with native species. Very little is known about the long-term success of native vegetation establishment on mined lands and the ability of rehabilitated vegetation to cope with future disturbances, and therefore work needs to be conducted on the decommissioning of mine sites in arid pastoral regions and on their resilience to grazing.

4.7. Conceptual Model of the Progressive Ecological Rehabilitation

The conceptual model that highlights the links between the success indicators of progressive ecological rehabilitation is presented in **Figure 19**.

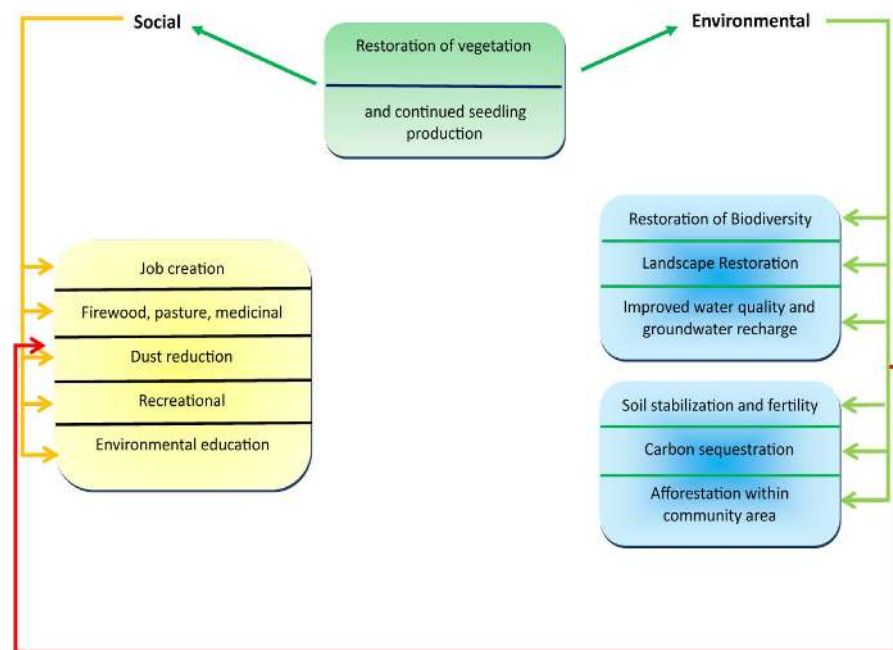


Figure 19. Conceptual model of the progressive ecological rehabilitation at Twangiza

These successes are directly linked to environmental aspects which in turn entrain social aspects.

5. Conclusion

The purpose here was to evaluate scientifically whether the planned ecological restoration objectives have been reached at Twangiza. The most successfully restored sites are located around the mine process plant due to optimal monitoring, as indicated by vegetation cover and growth. The Cinjira and Kadubo road sites did not work well due to multiple sabotages by some local community members. In fact, most of the objectives were well achieved. The community sensitization exercise may be rated at 65% - 70% success. The strengths are indicated by the biodiversity richness and the cover of the sites, with the subsequent improvement of the landscape, the reduction of erosion, the windbreak, and animal recolonization. Many more species have grown up, and more rapidly, at lower altitudes

(1900 m) than at higher altitudes (2200 m and above). *Pinus patula*, *Grevillea robusta*, and *Hagenia abyssinica* stood out for their strong growth at higher elevations (2300 - 2700 m asl). *Hagenia abyssinica* is known as an upland species. *Ficus thonningii* is the largest tree (max 280 cm collar diameter), followed by *Acacia melanoxylon* and *Maesopsis eminii*. The tallest trees were, respectively, *Maesopsis emini*, *Cedrela serrulata*, and *Acacia melanoxylon* (35 - 45 m), followed by *Ficus thonningii*. Every time the indigenous species grow up in the rehabilitation scheme, the local community lashes them out for use, claiming that they have grown naturally and that the mining company has nothing to say about their growth. Grazing by domestic animals (cows, goats, and sheep) is the predominant community use. Another rare commodity is firewood. This activity increases when the project embarks on regular tree pruning, which is beneficial for rapid tree growth. Local farmers also use pruned sticks as supports for volubile beans. Herbaceous plants, especially *Muhlenbergia capillaris* and *Brachypodium retusum*, are used as roof construction and floor cover inside thatch houses, where they act as temperature control. Some of the plants are used for medicinal purposes.

Our recent results on surface and groundwater, microclimate and air dust dynamics, and animal recolonization further showed that some of the major expected benefits of mine reclamation, including landscape restoration, water quality improvement, wildlife habitat rehabilitation, water and soil conservation, dust and air pollution control, carbon storage, and economic benefits, have been granted to some extent on the afforested 100 hectares rehabilitated within the core sites and at least 757 ha within the general communities in the mine vicinities. Landscape restoration is granted in the afforested area. In this way, reclamation reduced the visual impact of inactive mines and restored the natural aesthetics of the area. In contrast, during the baseline study, Bytebier et al. (2008) estimated that 90% of the land had been transformed by anthropogenic activities. Ecological rehabilitation stands as an efficient tool for environmental education and law improvement, as well as for the continuous promotion of local afforestation.

Authorization

This paper was authorized for publication by Twangiza Mining SA through the authorization letter dated December 1, 2023.

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identification.

Conflicts of Interest

The authors declare no conflict of interest for this paper.

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