Reclamation of lead/zinc processing wastes at Kabwe, Zambia: a phytogeochemical approach

B. Leteinturier[a*], J. Laroche[b], J. Matera[a] and F. Malaisse[a]

The lead/zinc mining industry of Kabwe (Central Province of Zambia), in operation from 1906 to 1994, generated metalliferous slag heaps covering an area of over 75 ha. The slag heaps are responsible for aerosol emissions with a high heavy metal content over the mine townships of Kasanda and Chowa, resulting in health risks for the local population. In this phytogeochemical investigation, soil samples showed very high lead, zinc and copper concentrations in topsoil. Plant surveys identified 39 taxa, including several tropical and metalloresistant weeds. We concluded that phytostabilization was the only suitable management method for the area. Plant species recommended for phytostabilization are *Indigofera spicata, Melinis repens, Cynodon dactylon, Aristida adscencionis* and *Pennisetum setaceum*.

Introduction

Mining industries specializing in the extraction and processing of ore with a high heavy metal content inevitably degrade the environment by contributing to atmospheric, water and terrestrial pollution. Slag heaps have a double effect as a result of the surface contamination and degradation of the landscape.[1] Central southern Africa has been, and still is, the site of intense mining activity. The main metals mined are copper, lead, zinc, cobalt, cadmium, gold and chrome; among these, lead poses the greatest health risk. In this context, there has been increasing awareness of the value of adopting ecological solutions such as land rehabilitation and re-vegetation of toxic sites. This approach has been adopted at the study site in Kabwe, Zambia.

Geographical context

Located in the heart of the Central Province, Kabwe is 150 km north of the Zambian capital, Lusaka, situated at 28°25′51″E, 14°28′00″S, at an altitude of 1190 m (Fig. 1). The site is on the right of the road, when travelling from Lusaka, at the entrance to the town of Kabwe and is a blackish slag heap towering above the mining infrastructure. The area related to mining activities covers some 78 ha.

The climate of the Central Province belongs to the Cw type of the Köppen classification. The ombrothermic diagram of Kabwe established by Walter and Lieth[2] (Fig. 2) shows the alternation of a rainy season from November to April and a dry season the rest of the year. The mean annual temperature is 20.7°C and the total mean annual precipitation is 938 mm.

During the rainy season, rainfall often occurs as storms and heavy rain and more rarely as continuous rainfall. The dry season comprises two quite distinct periods: one cold from May to August (low nocturnal temperatures, with occasional ground frost), the other hot from September to the beginning of November, when the progressive increase in temperature is accompanied by higher atmospheric humidity.

Kabwe is the provincial headquarters of the Central Province and has approximately 147 000 inhabitants.[3]

The mining industry

The mining industry of Kabwe, formerly known as Broken Hill, is the oldest in Zambia. Quarrying started before 1906. The mineral bodies at Kabwe consist of a core of sulphide ore (galena and sphalerite with minor pyrite) surrounded by a sheath of oxidized ores, mainly silicates, oxides and carbonates of lead, zinc and iron with subsidiary vanadium and copper. The sulphide ore averages about 12% lead, 34% zinc and the silicate 8% lead and 23% zinc. In 1977, ore reserves were 2.40 million tonnes.[4] About 25 minerals were extracted by underground mining; ores contained principally large amounts of lead and zinc and lesser quantities of silver and cadmium.[4] All mining activities officially ceased in 1994. Since then, the authorities have been involved in an environmental rehabilitation programme.

In some countries, lack of financial resources has led to the operation of polluting industries, resulting in potential health hazards and environmental degradation.[5] At Kabwe, dust particles containing heavy metals from surface slag heaps as well as smoke from factory chimneys (Fig. 3), are responsible for health problems encountered by the local population. A surveillance programme was set up in 1994 by the directors of the mine. Blood tests were carried out on 866 people, and each year, lead content was measured in the blood of young children, aged 2 to 5 years, living in the nearby townships of Kasanda and Chowa.[6]

In 1973/74, atmospheric lead concentrations in Kasanda Township, approximately 2 km northwest of the smelter, reached 145 $\mu g\ m^{-3}$ and soil concentrations of 2400 $mg\ kg^{-1}$ were recorded. In this area alone, which has a population of about 10 000, 27 cases of lead poisoning in children aged between 10 and 30 months were recorded between 1971 and 1973.

Since the end of the mining activities in Kabwe in 1994, the health risks of the local population and environmental degradation have become major issues, which are being addressed by the Kabwe Mine Closure Party, formed in April 1994.[6]

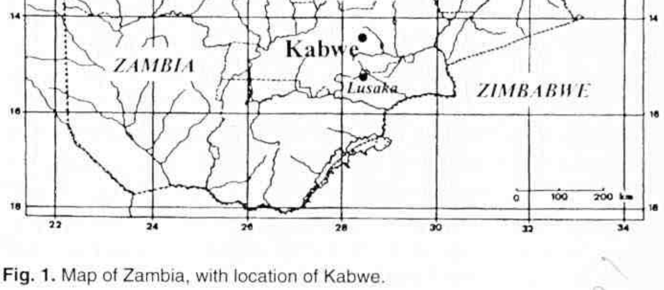

Fig. 1. Map of Zambia, with location of Kabwe.

[a]Laboratoire d'Écologie, Faculté Universitaire des Sciences Agronomiques, Passage des Déportés, 2, B 5030 Gembloux, Belgium.

[b]Unité de Géopédologie, Faculté Universitaire des Sciences Agronomiques, Avenue du Maréchal Juin, 27, B 5030 Gembloux, Belgium.

*Author for correspondence. E-mail: leteinturier.b@fsagx.ac.be

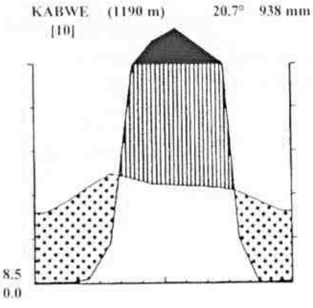

Fig. 2. Ombrothermic diagram for Kabwe (after ref. 2).

Material and methods

Sampling. Two plant inventories were carried out for each ecological biotope, the first one in the early dry season (end of April 1998), the second at the beginning of the rainy season (November 1998). Voucher specimens have been deposited in the herbarium of the Belgian National Botanical Garden at Meise (BR).

Furthermore, in April 1998, each substratum was sampled according to one of the following methods: Composite samples consisting of five sub-samples, distributed over the entire area of the unit, were used for landscape units B, C and E. Only the topsoil (0–10 cm) was sampled. For units H and G, samples were selective, comprising the substratum closely linked to the root system of individual plants.

Analysis. The lead, zinc and copper fraction soluble in aqua regia was determined for the substratum samples. The extraction solution was a mixture of the acids HCl (2:3) and HNO_3 (1:3). Flame atomic absorption spectrophotometry was used to measure the elements. This method (NF ISO 11466)[7] is used in various European countries to estimate the content of heavy metals in soils or sewage sludges. Aqua regia digestion is easily performed and the Commission of the European Community Bureau of Reference (BCR) provides certified reference soils that can be used to validate the extraction procedure.

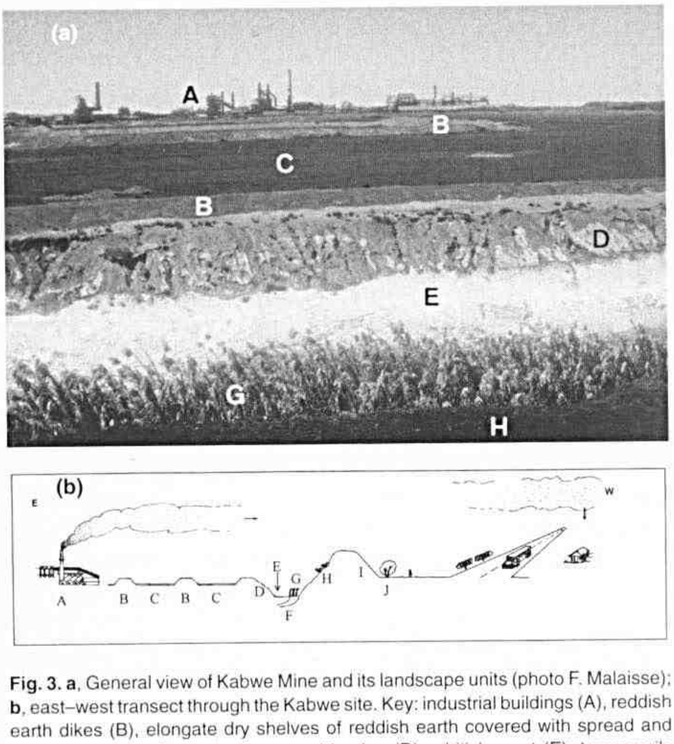

Fig. 3. a, General view of Kabwe Mine and its landscape units (photo F. Malaisse); **b**, east–west transect through the Kabwe site. Key: industrial buildings (A), reddish earth dikes (B), elongate dry shelves of reddish earth covered with spread and compacted slag (C), a slope covered in slag (D), whitish crust (E), temporarily flooded depression (F), humid zone colonized by *Phragmites mauritianus* (G), unstable mobile bank composed of blackish slag (H), and peripheral transition area which is sloping at first (I), then flat (J).

Results

Landscape units. The site studied is deeply scarred by past mining activity. Based on the relief and vegetation, several landscape units have been identified (Fig. 3).

Substrates. Lead and zinc concentrations were very high (Table 1) and revealed severe contamination. Lead concentrations seemed to vary among landscape units; the highest value was obtained for the red dyke (B) and the lowest for the white crust area (E). Zinc concentrations were fairly similar at all sites.

Copper concentrations were high and exceeded the range of values (20–62 mg kg^{-1}) observed in French soils.[9] The Kabwe values were nevertheless lower than those observed in the copper-bearing layer at Etoile Mine (Democratic Republic of Congo), where the soil contains 36 000 mg Cu kg^{-1} (ref. 10). The substratum of the white crust area (E) was characterized by a copper content 10–20 times smaller than that of the other areas.

Flora. The plant species were distributed in the landscape units as follows (Table 2):

B. The red earth of the dyke is colonized by two closed layers at the base, the lower area by *Digitaria sanguinalis*, the upper by *Cynodon dactylon*.

C. A large grey shelf covering the main part of the site is characterized by discontinuous sparse, but diverse vegetation.
The following species occurred:
- *Indigofera spicata* has a creeping habit; each individual forms a circular carpet of 50 cm or more in diameter. The ecological niche formed by this carpet favours the establishment of others species, such as *Euphorbia hirta* and *Tridax procumbens;*
- some other species also show a creeping habit, notably *Helichrysum argyrosphaerum;*
- several Poaceae in weak tufts: *Pennisetum setaceum, Melinis repens, Aristida adscensionis* and *Eleusine indica;*
- a number of Asteraceae, mainly *Ageratum conyzoides, Bidens oligoflora, Bidens pilosa, Flaveria trinervia, Neojeffreya decurrens, Tithonia rotundifolia, Vernonia ambigua* and *Vernonia erinacea.*

E. White crust area: without any vegetation.

F. Seasonally flooded unit; filamentous and mucilaginous algae, such as *Ulothrix variabilis* and *Cylindrocyotis brebissonii*, occur in channels.

G. Humid area with a 'soil' of soft consistency: widely dominated by *Phragmites mauritianus*, which forms a hydrophyte belt with isolated occurrences of *Cyperus alternifolius.*

H. Moving slope: two species occur sparsely here, *Pennisetum setaceum* and isolated stalks of *Celosia trigyna. Argemone mexicana* (Papaveraceae) and an unidentified species of Euphorbiaceae (LMM 149) occur sporadically.

J. The boundary transition area forms a contaminated ring, called 'poisoned dambo'.[11] *Bauhinia petersiana, Lantana camara, Nicandra physalodes* (which reaches 2 m here, whereas the individuals in unit C are very stunted), *Rumex usambarensis* and *Amaranthus dubius* grow in this area.

Table 1. Concentration of lead, zinc and copper (mg per kg dry matter) in the samples from the old mining site of Kabwe as determined in the aqua regia-soluble fraction.

Landscape unit	Pb	Zn	Cu
B	42 200	57 558	2 320
C	26 200	51 388	1 636
E	4 900	51 640	126
G	25 000	45 576	1 126
H	35 400	64 740	2 290

Table 2. Plant species, voucher specimens (collected by Leteinturier, Malaisse and Matera and deposited in BR), their origin and ecology[1,12–16] and the landscape unit(s) in which they occur.

Specimen number	Species	Family	Common name	Origin	Growth habit	Ecology	Landscape unit
156	*Achyranthes aspera* L.	Amaranthaceae	Burweed	Uncertain origin	P	Perennial weed in shade conditions	C
158	*Ageratum conyzoides* L.	Asteraceae	Invading ageratum	South America	A	Common weeds of annual crops and roadsides	C
151	*Alternanthera caracasana* Humb., Bonpl. & Kunth	Amaranthaceae		Tropical America	P	Roadsides, fallow fields	C
150	*Amaranthus dubius* Mart. ex Thell.	Amaranthaceae	Pigweed	Tropical America	A	Frequent on disturbed soils	J
119; 296; 473	*Argemone mexicana* L.	Papavaceae	Yellow-flowered Mexican poppy	South America	A – B	Pioneer of recently cleared sites	H, I
136	*Aristida adscensionis* L.	Poaceae	Annual free awn	Indigenous	A	Pioneer on disturbed and bare soils	C
161	*Bauhinia petersiana* Bolle	Caesalpiniaceae		Indigenous	P	Wooded grasslands	J
142; 480	*Bidens oilgoflora* (Klatt) Wild	Asteraceae		Indigenous	A	Fallow fields and metalliferous waste areas	C
141	*Bidens pilosa* L.	Asteraceae	Common blackjack	South America	A	Common in crops and disturbed areas	C
135	*Catharanthus roseus* (L.) G. Don	Apocynaceae		Tropical America	P	Escaped from gardens	C, I
118; 485; 506	*Celosia trigyna* L.	Amaranthaceae		Indigenous	A	Roadsides, fallow fields, crops	H
497	*Cleome monophylla* (Klatt) Willd.	Capparaceae	Single-leaved cleome	Indigenous	A	Common weed of crops	C
157	*Convolvulus sagittatus* Thunb.	Convolvulaceae	Wild bindweed	Indigenous	P	Weed of waste places	C
124	*Cynodon dactylon* (L.) Pers.	Poaceae	Couch grass	Indigenous	P	Widely distributed weed on disturbed areas	B, H
121	*Cyperus involucratus* Rottb.	Cyperaceae			P		
140; 502	*Elusine indica* Gaertn.	Poaceae	Indian goosegrass	Probably exotic	P	Ruderal sites, roadsides, trampled areas	C
146	*Euphorbia hirta* L.	Euphorbiaceae	Red milkweed	Tropical America	A	Weed on bare, exposed areas	C
147	*Flaveria trinervia* (Spreng.) Mohr	Asteraceae	Smelter's bush	Uncertain origin	A	Annual weed of waste places	C
481	*Gomphrena celosioides* Mart.	Amaranthaceae	Prostrate globe amaranth	Tropical America	P	Reclaimed soils, waste ground	C
133	*Helichrysum argyrosphaerum* DC.	Asteraceae			A		C
125	*Indigofera spicata* Forssk.	Fabaceae		Indigenous	P	Weed	C
155	*Ipomoea cairica* (L.) Sweet	Convolvulaceae	Coastal morning glory	Indigenous	P	Minor weed	C
148	*Lantana camera* L.	Verbenaceae	Common lantana	Tropical America	P	Major weed, able to form dense, impenetrable thickets	J
489	*Melinis repens* (Willd.) Zizka	Poaceae	Natal red-top	Indigenous (probably)	P	Short-lived perennial weed of roadside and waste places	C
159	*Neojeffreya decurrens* (L.) Cabrera	Asteraceae			A		C
152	*Nicandra physalodes* (L.) Gaertn.	Solanaceae	Apple of Peru	Peru	A	Weeds of crops and waste areas	C, I, J
129	*Nidorella resedifolia* DC.	Asteraceae		Indigenous	A	Annual weed	C
117; 298	*Pennisetum setaceum* (Forssk.) Chiov.	Poaceae	Fountain grass	Northern Africa	P	Steep stony slopes at excavations	H, I
120; 302	*Phragmites mauritianus* L.	Poaceae	Lowveld reed	Indigenous	P	In wet places and water up to a depth of 1–2 metres	G
160	*Rumex usambarensis* (Dammer) Dammer	Polygonaceae		Indigenous	P	Exposed rocky slopes	J
144	*Solanum incarnum* L.	Solanaceae	Thorn apple	Indigenous	P		C
145	*Solanum nigrum* L.	Solanaceae	Black nightshade	Indigenous	P	Common in fields	C
153	*Tagetes minuata* L.	Asteraceae	Mexican marigold	South America	A	Weed of crops	C
126	*Tithonia rotundifolia* (Mill.) Blake	Asteraceae	Red sunflower	South America	P	Dense colonies on roadsides and waste places	C
312	*Tricliceras longipedunculatum* (Mast.) Fernandes var. *longipedunculatum*	Turneraceae		Indigenous	P	Grasslands in southern Africa, roadsides	J
131; 501	*Trichodesma zeylanicum* (Burm. f.) R. Br.	Boraginaceae	Late weed	Europe, Asia	P	Cultivated lands, roadsides and waste places	C
138	*Tridax procumbens* L.	Asteraceae	Tridax daisy	Central America	A	Weed on roadsides and waste places	C
127	*Vernonia ambigua* Kotschy & Peyr.	Asteraceae		Indigenous	A	Roadsides and fields	C
128	*Vernonia erinacea* Wild	Asteraceae		Indigenous	A	Sandy savannas	C

Growth habit: A: annual; B: biennial; P: perennial.
Landscape units: see caption of Fig. 3.

Discussion

A recent survey of English and Welsh soils[8] (extraction performed with aqua regia) showed that the average content of the top horizon of cultivated soils is 40 mg Pb kg^{-1} and 82 mg Zn kg^{-1}. In France at Mortagne-du-Nord (Département du Nord), as in Kabwe, high concentrations of lead and zinc (10 300 and 22 422 mg kg^{-1} respectively) are observed in the topsoil (0–3 cm) of metalliferous grassland near the slagheap of an old zinc plant.[9]

Despite the artificial origin of several substrata, and soils characterized by physically and chemically extreme conditions, the flora comprises 39 indigenous and exotic taxa. However, three landscape units showed a very low diversity, in response to a restricted surface area and very severe conditions, both chemically (unit B) and hydrologically [units F (seasonally flooded) and G (reed community).

Several tropical and metalloresistant weeds were identified. They belong to different ecological groups, mainly as ruderal plants (*Ageratum conyzoides, Alternanthera caracasana, Celosia trigyna, Eleusine indica, Tricliceras longipedunculatum* var. *longipedunculatum* and *Vernonia ambigua*), as weeds colonizing disturbed sites (*Amaranthus dubius, Aristida adscensionis,* and *Cynodon dactylon*) and as weeds colonizing waste areas (*Argemone mexicana, Bidens oligoflora, Convolvulus sagittatus, Flaveria trinervia, Gomphrena celosioides, Melinis repens, Nicandra physalodes, Tithonia rotundifolia, Trichodesma zeylanicum* and *Tridax procumbens*).

Three management and rehabilitation strategies were considered for the metalliferous sites at Kabwe:

- Revegetation with the original natural vegetation was regarded as unsuitable, despite its having been suggested elsewhere.[17] Such a project depends primarily on knowledge of the original indigenous flora and on the existence of suitable plants. The absence of a natural vegetation unit of the savanna type occurring on metalliferous outcrops[18] would make it virtually impossible to achieve.
- Phytoextraction was rejected for several reasons. First, the low density of plant cover at Kabwe indicates that it will not be possible to establish high enough plant densities for phytoextraction to be successful. Second, the absence of information regarding a high-performance tropical lead hyperaccumulator[19] must be borne in mind. Moreover, some difficulties of potential phytoextraction of lead have been noted.[20]
- Phytostabilization is the only suitable strategy. Appropriate plants can be selected on the basis of available phytosociological data for *Mesobrachystegion* on red soils,[21,22] which is the most diverse floral climax observed within Zambian miombo woodlands.

The origin[23] and ecology of the species found at Kabwe (Table 2) will inform the selection of species. Noxious taxa, such as *Lantana camara,* should be carefully monitored and possibly eradicated.

The following plant species are considered suitable for phytostabilization:

- *Indigofera spicata,* which forms a niche favourable for the establishment of other species and has an abundant fruit yield ensuring a constant supply of seeds;

- *Melinis repens* is a good soil stabilizer that provides an effective cover in disturbed areas;[12]
- *Cynodon dactylon* is a valuable grass for combating erosion;[12]
- *Aristida adscensionis* is a useful accessory species;
- *Pennisetum setaceum*, although an exotic species, would be suitable for stabilization of rocky slopes[13] and re-vegetation of flat areas. Its vigour on the site at present and its metal-tolerance both mitigate for the use of this species.

The method of substrate analysis did not provide information on the mobility of lead, zinc and copper or of their bioavailability for the plants. Analyses of plant samples to assess their trace element content would make it possible to assess the bioavailability of these elements. It might also be advisable to determine the bioavailable fraction of the elements in the soil and to compare them with those of the neighbouring open forest soil.[22]

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