Botanical Diversity and Heavy Metal Content in the Residue Matrix and Plants at the Moravia Dump in Medellín, Colombia

Diversidad Botánica y Contenido de Metales Pesados en la Matriz de Residuos y los Vegetales en el Basurero de Moravia en Medellín, Colombia

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Abstract. *Floristic characterization, plant tissue and residue matrix (RM) analysis were conducted to establish the extent of heavy metal (HM) pollution of the Moravia dump at Medellín, Colombia, a site that was inhabited by more than 17000 people since 1984. More than 65 plant species (28 families) were identified, most of which were herbaceous. Content of HM in the (RM) was determined in 14 different RM samples varied greatly among them, reaching 121 and 9600 mg/kg of Hg and Pb respectively. Mean content of HM (mg/kg) in the RM had the following pattern: Pb > Ni > Cr > Hg > Cd. Uptake of HM from the RM to plants was evident in most sampled species, with concentrations of Pb, Cr, and Hg reaching maximum values of 1.0, 123.7, 263.7 mg/kg of Hg, Pb and Cr respectively. However,* ***Lepidium virginicum*** *excluded, estimated bioconcentration factors were not greater than 1.0. Given their adaptation,* ***Bidens pilosa****,* ***Urochloa maxima*** *and* ***L. virginicum,*** *appear to be suitable for the revegetation of Moravia. Twenty-four years after its closure, HM content in Moravia continue to be high and the local flora actively takes up HM. Since other studies have shown that in Moravia there is still production of lixiviates and that there is an active heavy metal transference to the local Moravia fauna, it is imperative to implement adequate control measures in order to control HM contamination at this site.*

Key words: Heavy metal, pollution, revegetation, waste, wild flora.

Resumen. *Con el fin de establecer el nivel de contaminación por metales pesados (MP), se llevó a cabo una caracterización florística y análisis de la matriz de residuos (MR) y muestras de tejidos vegetales en el morro de basuras de Moravia en Medellín, un antiguo botadero de basuras habitado desde 1984 por más de 17.000 personas. Se identificaron más de 65 especies vegetales, la mayoría de ellas herbáceas, agrupadas en 28 familias. El contenido de MP en 14 diferentes muestras de MR varió considerablemente, yendo de 121 y 9.600 mg/kg de Hg y Pb, respectivamente. El contenido promedio de MP en la MR siguió el orden: Pb > Ni > Cr > Hg > Cd. Hubo absorción de MP en diversas especies vegetales, alcanzando valores máximos de 1,0; 123,7; 263,7 mg/kg en el caso de Hg, Pb y Cr, respectivamente. Sin embargo, a excepción de* ***Lepidium virginicum****, los valores de factores de bioconcentración estimados no fueron mayores que 1.0. Dada su cobertura y adaptación a las condiciones del antiguo basurero,* ***Bidens pilosa, Urochloa maxima*** *y* ***L. virginicum,*** *se evidencian como especies adecuadas para el proceso de revegetación del Morro de Moravia. Aún después de 24 años desde la clausura del basurero, se encontraron altos contenidos de MP tanto en la MR como en los tejidos vegetales muestreados. Dado que estudios complementarios a este han mostrado que aún existe producción de lixiviados en Moravia y que existe transferencia activa de metales pesados a la fauna presente en Moravia, existe la necesidad de implementar medidas de reducción de la contaminación en este sitio.*

Palabras claves: Metales pesados, contaminación, revegetación, residuos, flora nativa.

Dumps and landfills located near towns and cities have been a feature of public sanitation. These disposal sites have served as the final destination for a wide range of organic and inorganic materials; in some of these sites soil and groundwater have become polluted through the incidental or intentional disposal of persistent and hazardous industrial organicchemicals or heavy metals (HM) (Miller and Clesceri, 2003). Composition-wise, open dumps and landfills are commonly referred as heterogeneous, as the result of the disposal and decomposition of wastes from different sources which contain a broad range of natural and xenobiotic molecules (Nagendran *et al*., 2006). In Colombia, 69% of the towns with less than 12.000 inhabitants and 40% of the cities with more than 500.000 inhabitants, still used open dumps by 2002 (Ministerio del Medio Ambiente, 2002), a practice that has been associated with human health

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problems and pollution of water, soil and air due to the generation of leachates, increased presence of disease vectors, possible geological instability and changes in fauna and flora composition.

Both landfills and dumps constitute a global challenge, as in such places, contaminants commonly reach high and sometimes dangerous concentrations. Among those contaminants, HM are considered a serious risk to human health and the environment since they can accumulate for long periods of time and they may enter the food web (Nedelkoska and Doran, 2000). Generation of municipal wastes and industrial activities are considered the main source of HM pollution (Banat *et al.,* 2005).

Once waste dumps are closed, there is a need to follow the environmental evolution of these structures, because sealing the site does not guarantee the removal of risks to the environment (Lopes *et al*., 2006). A set of management measures need to be implemented, which include controlling superficial water movement, surface erosion and generation and migration of lixiviates. Naturally occurring vegetation in landfills and dumps can play an important role in the control of erosion, the reduction of contaminants and the improvement of the aesthetic value of such places. The study of plants growing on landfills and dumps can be of value as it can lead to the identification of species) with phytoremediation potential to be used in restoration processes (Nagendran *et al*., 2006. The former open dump at Moravia in Medellín, Colombia, is considered to be a risk for the human population, a source of contamination for the Medellín river and a threat to the environment. Medellín municipal authorities started a series of studies that aimed to assess the current pollution level and to determine the best management actions to take at the Moravia dump. Among these activities, reallocation of the inhabitant families is top priority (Municipio de Medellín, 2004), followed by the restoration of this hill and nearby areas and its possible incorporation as a public space. As part of this macro project, the current study was conducted with the purpose of performing the floristic characterization of the Moravia dump area, as well as, the characterization of soils and plants in relation to their HM content.

MATERIALS AND METHODS

Site description. The Moravia dump (6° 13´ N, 75° 34´ W) is situated approximately 40 m from the Medellín river margin (Figure 1) and operated from 1970 to 1984, receiving about of 100 ton/day of industrial, domestic and medical residues (Integral, 2000). This area became progressively inhabited and by the end of 1983 more than 17.000 people were living there, with 1.013 families still residing there today.

Figure 1. Localization of the Moravia dump in Medellín, Colombia.

The matrix of residues has become a hill of 7.6 ha with a maximum height of 42.5 m from its base. On its sides, the hill presents slopes gradients of 8-10° (South-North direction) and 20-25° (East-West direction). The residue matrix at Moravia dump contains a great proportion of plastics, broken glass, concrete, wood, metals, semi degraded fabrics and organic matter. Superficial layers (0-40 cm) also contain various types of pipes for drinkable and residual water transport around the houses. As it is common in most open dumps, Moravia does not have a drainage system or a system for the treatment of leachates. According to 2008 calculations, the dump is producing a total leachate effluent of 1.78 m^3/day (Sánchez *et al.*, 2009).

Given the evident risk for the health of Moravia inhabitants, municipal authorities started the progressive reallocation of families. Such reallocation permitted the unoccupied plots to be colonized by herbaceous species, initiating a revegetation process (spontaneous and man influenced, as some inhabitants grew different types of plants). This process is not homogeneous to all the empty plots around the dump, and for those plots first revegetated, the process had reached a maximum of two years at the moment that this study took place. In two of these empty plots, and prior to this study, Medellín authorities placed a 20 cm clay cover of an unknown source, in an attempt to reduce soil erosion and improve site aesthetics. For this reason, in this study we will be refereeing to two types of plots: residue matrix (RM) of Moravia and RM covered with clay. As the first activity, a complete survey of the total area in a revegetation process (3648.9 m^2) was conducted and this included the characterization of 14 sampling plots, which differed in size, slope and extent of revegetation and were randomly distributed within Moravia.

Floristic characterization. Floristic characterization was carried out between February and March in 2008. First, the entire dump area was surveyed and all plots with an evident revegetation process were described in terms of their area, nature of substrate (RM and RM with clay) and leachate exposure. After this was completed, a floristic inventory was carried out. At each plot, flowering plant specimens were collected and pressed using firm cardboards and given a code. Collected specimens were sent to the Medellin Botanical Garden Herbarium Joaquin Antonio Uribe, for the taxonomic identification. At the Medellín Botanical Garden Herbarium, a voucher number was issued for each species identified and the collection kept for further reference. Since they were readily identifiable, samples for very common plant species such as *Cucurbita maxima* (winter squash plant) and *Cynodon dactylon* (Bermuda grass) were not sent to the Herbarium for identification.

Plant cover determination. As the present study has been the first floristic characterization conducted in Moravia, it was important to report the abundance of the different strata and plant species that were revegetating the former dump. It was also important to gather information on biomass production of plants growing in Moravia, since these measurements could give an idea of the Moravia conditions or further revegetation process. To determine the cover area for each of the plant species growing at the Moravia dump, a modification of the Matteucci and Colma (1982) methodology was followed: Plant cover for a given plant species at each plot: Plots were divided into squares of ca. 1 m^2 so as to facilitate visual estimation of the area covered by a given plant species, as a percentage of the area on each plot. This determination was only done for the most abundant plant species. Once this variable was recorded, the determination of minimum and maximum values among the surveyed plots was conducted.

Plant cover for a given plant species in Moravia. Once the total of the revegetated plots were inventoried, the area covered by a given plant species was calculated as the relation between the area covered by such species and the total area sampled. This value was expressed as percentage.

Dry matter (DM) production. The DM production was estimated for the most abundant plant species (those with more than 3% of plant cover) according to the previous work conducted for plant cover. Samples of the plant species selected were collected manually registering the cover area of each species using a square of 0.5 X 0.5 m. Aerial tissues were collected in triplicate and dried out at 60 ºC in a forced-air oven for 48 hours. Production of DM was estimated as g DM/m^2.

Heavy metal content in the residue matrix and plant material. Since initial analysis of the RM and plant samples collected at Moravia showed that the HM of greater importance (mg/kg) were Pb, Cr, Cd and Ni, analytical determinations for most samples at this study focused in these four metals.

For the determination of HM in RM sample, a total of 14 samples were collected from the same plots where floristic characterization had been previously conducted. In each plot two or three RM samples were taken and transported to the laboratory. Once there, samples were thoroughly mixed with the help of a small shovel and a representative RM sample was then obtained for each plot. Care was taken to ensure that elements such as glass and plastic fragments, pieces of clothing and other non-degraded materials of anthropogenic origin were taken out from those samples. The resulting samples were air-dried at room temperature for seven days. In addition to the samples collected at Moravia, a soil sample was collected in a nearby, non-Moravia plot, separated some 40 m from the base of the dump and also close to the Medellín river, which was used as a control.

Determination of HM in plant tissue was only carried out in samples of plant species with plant cover greater than 3%. The majority of them, depending on availability, were collected in different plots in the Moravia dump. Plant samples (including roots and aerial tissues) were collected and taken to the laboratory. Before HM determination, these samples were gently rinsed with tap water and then air-dried at room temperature during seven days. Samples were constituted by the roots and aerial tissues of two individual plants.

Determination of total HM content both in RM and plant samples was carried out at the GDCON Laboratory, University of Antioquia following standard procedure methods: EPA SW-846 3050B for determination of Pb, Cr, Cd and Ni (EPA, 1996) and EPA SW-846 7471B for determination of Hg (EPA, 1998). To do this, when assaying for Pb, Cr, Cd or Ni, 1 – g samples were subjected to calcination at 450 °C and the resulting ashes were subjected to acid digestion using a 1:1 mixture of HNO_3 and $HClO_4$. When assaying for Hg, a 1:1 mixture of H_2SO_4 and $KMnO_4$ was used for sample digestion and no sample calcination was performed. Determination of HM concentration was carried out in a GBC 932 atomic absorption spectrophotometer, with HM content estimated as mg/kg of DM. According to the HM determination method used, the detectable limits (mg/kg) were 0.001 for Hg, 0.125 for Pb, 0.250 for Cr and Ni and 0.050 for Cd. For the value of discussion, and using the DM production and the HM concentration, the ability of selected plants species to extract HM was calculated assuming they were used in a single-crop approach. In addition to the HM determinations, four RM samples were also analyzed for physical chemical properties following standard procedures: texture was determined by Bouyoucos methodology (1936), pH was determined in water (1:1), Exchangeable Ca^{2+}, Mg^{2+}, K^{+} contents were determined by the ammonium acetate method (Schollenberger and Simon, 1945), the effective cation exchange capacity (ECEC) was estimated as the sum of Ca^{2++} Mg^{2++} K^{2++} in cmol/kg, and organic matter (OM) was determined according to the method reported by Walkley and Black (1934).These analyses were carried out as they may contribute to explain HM bioavailability.

Estimation of bioconcentration factors (BCF). A measurement of the availability and transference of HM from soil to plants and thus an indicator of the possible entrance of HM to the food web is the bioconcentration factor (BCF), calculated as the ratio between HM content in plant tissue and that one in the substrate. Considering the high heterogeneity of the Moravia dump, RM samples and since it was impossible to find all plants growing in the same plots, we only calculated BCF for those species where the paired (RM-plant tissue) HM determination was possible. Similarly, we only calculated BCF for Pb and Cr absorption.

RESULTS AND DISCUSSION

A total of 14 unoccupied plots were surveyed. Since the main cause that promoted the revegetation process was the progressive reallocation of inhabitants, physical characteristics of the unoccupied plots varied in area (60 to 649 m^2), plant cover (55 to 99.7%) and localization within the dump. Among the sampled plots, two had a clay layer deposited there by the municipal authorities.

Floristic characterization. Table 1 reports the families, plant species and the voucher number issued by the Medellín Botanical Garden Herbarium for each of the plant samples collected. In total, more than 65 plant species were identified, grouped into 28 botanical families. This total includes the species identified at the Botanical Garden Herbarium and those identified *in situ* (for example *Cynodon dactylon* and *Cucurbita maxima)*. Most of the species identified belonged to the families Asteraceae (9), Poaceae and Solanaceae (5), Cyperaceae and Malvaceae (4), Convolvulaceae and Euphorbiaceae (3). Among the species identified at Moravia there were tree species (*Spathodea campanulata*, *Senna occidentalis*, *Leucaena leucocephala* and *Persea caerulea)*, as well as shrubs (*Ricinus communis*, *Nicotiana glauca*, *Brugmansia arborea* and *Bunchosia armeniaca*), and the fruit bearing tree *Carica papaya*. Species belonging to the herbaceous stratum were the most abundant among all plant species identified at Moravia.

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Table 1. Families, species and voucher number for the plants identified at the Moravia dump. Medellín, Colombia.

Family	Especies	Registration code
Amaranthaceae	*Alternanthera albotomentosa* Suess	43888
	Amaranthus spinosus L.	43870
Asteraceae	*Acmella oppositifolia* (Lam.) Jansen	43832
	Ageratum conyzoides L.	43833
	Ambrosia cumanensis Kunth.	43866
	Bidens pilosa L.	43834
	Conyza bonariensis (L.) Crong.	43836
	Emilia coccínea (Sims) Sweet.	43835
	Erechtites hieracifolia (L.) Raf.	43839
	Gallinsoga ciliata (Raf.) Blake.	43837
	Tagetes patula L.	43838
Bignoniaceae	*Spathodea campanulata* P. Beruv	43841
Brassicaceae	*Brassica campestris* L.	43842
	Lepidium virginicum L.	43889
Caesalpiniaceae	*Senna occidentalis* (L.) Link	43844
Caricaceae	*Carica papaya* L.	43845
Caryophyllaceae	*Drymaria cordata* (L.) Willd.	43846
Chenopodiaceae	*Chenopodium ambrosioides* L.	43847
Commelinaceae	*Commelina diffusa* Burm. F.	43890
	Setcreasea purpurea Boom	43871
Convolvulaceae	*Ipomoea clavata* (G. Don) Van Oostroom	43848
	Ipomoea nil (L.) Roth.	43867
	Ipomoea tiliacea (Willd.) Chass.	43885
Cucurbitaceae	*Elateriopsis oerstedii* (Cogn.) Pitt.	43849
Cyperaceae	*Cyperus ferax* Rich.	43850
	Cyperus odoratus L.	43851
	Fuirena cf. umbellata Rottb	43852
	Mariscus flabelliformis Kunth	43853
Euphorbiaceae	*Euphorbia heterophylla* L.	43854
	Phyllanthus cf. niruri L.	43868
	Ricinus communis L.	43873
Fabaceae	*Crotalaria pallida* Ait.	43874
Geraniaceae	*Pelargonium cf. zonale*	43872
Lamiaceae	*Stachys micheliana* Briquet	43876
Lauraceae	*Persea caerulea* (Ruiz & Pavón) Mez	43891
Malpighiaceae	*Bunchosia armeniaca* (Cav.)DC.	43869
Malvaceae	*Hibiscus sabdariffa* L.	43877
	Malachra cf. alceifolia Jacq.	43878
	Malvaviscus arboreus Cav.	43879
	Sida rhombifolia L.	43880
Mimosaceae	*Leucaena leucocephala* (Lam.) De Wit.	43855
	Mimosa pudica L.	43857
Nyctaginaceae	*Mirabilis jalapa* L.	43858
Poaceae	*Eleusine indica* (L.) Gaertn.	43882
	Paspalum plenum Chase.	43862
	Pennisetum purpureum Schumach	43896
	Sorghum halapense (L.) Pers.	43894
	Urochloa maxima (Jacq.) R. Webster (Synm: *Panicum máximum* Jacq.)	43897
Phytolaccaceae	*Petiveria alliacea* L.	43859
	Phytolacca icosandra L.	43892
Plantaginaceae	*Plantago major* L.	43860
Polygonaceae	*Polygonum punctatum* Ell.	43861
	Polygonum segetum Kunth	43886
Portulacaceae	*Portulaca oleracea* L.	43881
Solanaceae	*Brugmansia arbórea* (L.) Lagerh.	43863
	Nicotiana glauca Graham	43898
	Nicotiana tabacum L.	43883
	Pyysalis peruviana L.	43864
	Solanum americanum L.	43865
Verbenaceae	*Verbena litoralis* Kunth.	43884

Table 2. Plant cover estimation for species growing at the Moravia dump. Medellín, Colombia.

Plant species	Number of plots	Plant cover (%)		
		Minimum	Maximum	Average
Urochloa maxima	11	0.81	71.07	24.74
Bidens pilosa	12	12.46	50.32	23.38
Cucurbita maxima	6	3.36	35.43	9.08
Alternathera albotomentosa	7	1.68	19.48	4.92
Ipomoea tiliacea	4	0.33	28.28	4.37
Amarathus spinosus	7	1,66	15.15	3.88
Nicotiana tabacum	6	0.17	25.97	3.25
Commelina diffusa	3	4.43	36.90	3.20
Eleusine inidca	1	12.94	12.94	2.47
Nicotiana glauca	7	0.14	12.36	2.37
Cynodon dactylon	1	21.86	21.86	2.19
Gallinsoga ciliata	3	5.63	6.47	1.92
Ipomoea nil	3	1.68	13.39	1.82
Leucaena leucocephala	6	0.37	6.88	1.31
Emilia coccinea	7	0.22	12.12	1.17
Sida rhombifolia	3	1.19	4.75	1.00
Cyperus ferax	1	16.81	16.81	0.95
Ricinus communis	4	0.46	6.72	0.73
Lepidium virginicum	3	0.79	1.74	0.61
Pysalis peruviana	2	0.41	10.42	0.58
Ageratum conyzoides	2	1.19	2.51	0.54
Chenopodium ambrosoides	1	2.59	2.59	0.49
Carica papaya	2	2.76	4.06	0.46
Ipomoea clavata	2	0.26	3.18	0.37
Verbena spp	2	0.26	3.17	0.34
Crotalaria pallida	1	2.85	2.85	0.30
Polygonum segetum	1	2.37	2.37	0.24
Portulaca oleracea	2	1.32	6.06	0.12
Senna occidentalis	2	0.08	0.79	0.09
Conyza bonariensis	2	0.22	1.28	0.06
Mimosa pudica	1	0.16	0.16	0.03
Plantago mayor	1	0.04	0.04	0.01

The composition of local flora, the germination and establishment probabilities are decisive for the formation of pioneer plant communities. Likewise, composition of vegetation on polluted sites depends on tolerance and avoidance mechanisms of colonizing plants (Dazy *et al.,* 2009). In this study, the predominance of herbaceous species observed in Moravia could obey to the fact that the survey was conducted during the early stages of revegetation.

Observations that the families with higher number of individual species were Asteraceae, Poaceae, and Solanaceae and the presence of the species *Bidens pilosa* (Table 1) and *C. maxima* coincide with previous reports on floristic composition in landfills and mine disturbed sites (Nagendran *et al*., 2006). Likewise, *Ageratum conyzoides* and *Cynodon dactylon* have been previously reported as dominant species in places contaminated with HM (Li *et al*., 2007; Remon *et al.,* 2005). In turn, the grass *Urochloa maxima* has been studied for its capacity to remediate soils with low levels of oil contamination (Hernandez y Pager, 2003).

Plant cover. Results are shown in Table 2, which includes the number of plots in which a given plant species was found and the minimum, maximum and average plant cover values (%). A total area of 3648.9 m^2 was surveyed in this study, from which 2842.7 m^2 corresponded to revegetated area.

Results showed that about 50% of sampled area was covered by the species *U. maxima* and *B. pilosa,* which were present in 11 and 12 out of the 14 plots sampled, respectively. In third place was the species *Cucurbita maxima*, with a cover of 9% which was present in six out of the 14 sampled plots. This edible species was initially planted by the Moravia inhabitants near their homes from where it spread to other areas.

Regarding the presence of trees, Chan *et al*., (1997) reported *Leucaena leucocephala* as a very common and predominant plant species in two landfills in Hong Kong, suggesting that this legume could be used in the revegetation of these sites. Likewise, Kasassi *et al*. (2008) reported the use of *C. dactylon* in the successful revegetation of a closed landfill in Northern Greece.

Plant dry matter production. Data for DM production is presented in Table 3. The highest DM production was observed with the grass *U. maxima* (7.4 kg DM/m^2), a value far greater than those found in all other plant species growing at the Moravia dump, which had a DM production ranging from 0.1 to 4.7 kg/m^2. Dry matter production varied greatly across the different sampling sites (Table 3) and this could obey to differences in fertility, physical and chemical RM properties among plots or to differences in plant growth stage. The sampling methodology used in this study was not intended to eliminate variations in any of these factors, thus the great variation here reported.

Table 3. Dry matter production (kg/m^2) of the plant species growing at the Moravia dump. Medellín, Colombia.

Plant species	Number of samples	Dry matter production (kg/m^2)	SEM
Urochloa maxima	2	7.40	6.41
Leucaena leucocephala	1	4.70	__
Pelargonium cf. zonale	1	1.10	__
Sida rhombifolia	2	0.44	0.24
Cynodon dactylon	4	0.34	0.16
Nicotiana glauca	2	0.31	0.01
Alternathera albotomentosa	4	0.31	0.12
Amarathus spinosus	2	0.26	0.11
Bidens pilosa	5	0.25	0.07
Lepidium virginicum	3	0.24	0.06
Cucurbita maxima	8	0.23	0.09
Iipomoea tiliacea	3	0.23	0.03
Chenopodium abrosioides	2	0.20	0.07
Ipomoea nil	4	0.19	0.06
Ageratum conyzoides	2	0.10	0.02
Commelina diffusa	3	0.08	0.02

The results (floristic characterization, plant cover and DM production), showed that Poaceae and Asteraceae were the predominant families at the Moravia dump. However, most of the plant species identified showed adequate adaptation to the Moravia conditions, judging by data on plant cover and DM production. In most cases, plant species were present in several plots, growing healthily with different phenological stages, and producing seeds in abundance. The absence of toxicity symptoms could obey either to low HM availability in Moravia, an explanation that may be the small fraction of total HM actually entering plant tissues or to the ability of plants growing at Moravia dump, to tolerate high contents of HM in growth substrate, an explanation that requires further testing, especially in the case of *B. pilosa, L. virginicum* and *E. coccinea*, the species with the highest concentrations of HM in their tissues.

***Physical and chemical RM properties*.** Data from four RM samples from the Moravia dump showed that pH varied from 7.0 to 7.6. Except the samples where RM was covered with clay which showed a clay loam texture, samples from Moravia showed a sandy loam texture. Effective cation exchange capacity (ECEC) varied from 21.9 cmol/kg (clay plot) to 32 cmol/kg. In turn, organic matter content ranged from 1% (clay plot) to 12.9 % (in RM samples). The values found for the physicochemical properties may suggest that HM accumulated in the RM in Moravia dump could be of low availability, although a higher number of samples should be accomplished in order to establish the extent of bioavailability in the Moravia dump.

Heavy metal content in Moravia dump RM. A total of 14 RM samples, corresponding to 10 samples from a depth of 0-20 cm and four samples from deeper layers (20-40 cm) were analyzed. Table 4 reports the number of samples analyzed and concentration (range, mean value and SEM) of Hg, Pb, Cr, Cd and Ni in those RM samples. Figure 2 (a-e) shows HM content in each plot sampled in the Moravia dump.

Table 4. Statistical parameters for total heavy metal concentration in the residue matrix samples of Moravia dump. Medellín, Colombia.

Descriptor	Content (mg/kg)				
	Hg	Pb	Cr	Cd	Ni
Number of samples	10	14	14	14	14
Concentration range (mg/kg)	<0.001 -121.3	2.86-9624	17.9-476.7	<0.05 -13.14	5.12-1689
Mean value (mg/kg)	16.63	2339.5	160.6	5.32	322.4
SEM	11.8	713.7	34.4	1.1	154.5
Reference Values[1]	0.020–0.625	10 – 30	14-70	0.07- 1.1	3–1000
Reference Values [2]	0.95	597.5	186.4	3.3	87.7
Reference Values [3]	NA	120	100	1	30

[1] Normal concentration range in agricultural soils, (World Health Organization, 2007)
[2] Mean Values reported by Tesfai and Dresher (2009)
[3] Maximum permissible limits, ASCP (2001).

The highest Hg content (121.3 mg/kg) was observed in the superficial layer samples obtained from the clay – covered plot. In contrast, RM samples from plots with no addition of clay showed lower (0.58 to 18.32 mg/kg) Hg content. A similar trend was observed with Ni, of which the highest content (about 1600 mg/kg) was observed in the 20-40 cm sample from the clay – covered plot, whereas RM samples with no addition of clay presented lower Ni content (from 45 to 153 mg/kg). Content of Pb and Cr in the RM samples showed high variation (from 2.86 to 9624 and from 17.9 to 476.7 mg/kg, respectively) and it was not possible to establish an association between HM content and plot characteristics. The content of Cd in RM samples did not vary as much as Pb and Ni did, with concentrations going from <0.05 to 39.0 mg/kg. Overall, the abundance of total HM in Moravia RM samples followed the next order: Pb > Ni > Cr > Hg > Cd. On the other hand, results showed that in the non-Moravia plot control, the contents of Hg, Pb, and Cr were within permissible limits (Hg: 0.58, Pb: 41.9, Cr: 62.2, Cd <0.05 and Ni: 5.1).

Total RM HM content in Moravia was compared to permissible limits for soils, amendments and composts according to the Colombian (ICONTEC, 2004) and Swiss (ASCP, 2001) regulations, limits reported by the World Health Organization (2007), as well as previously reported HM contents in landfill soils (Tesfai and Dresher, 2009). As shown in Table 4, in some cases these HM contents greatly exceeded the permissible limits established in both regulations. Contents of Hg, Pb and Ni were in very high concentrations, reaching in some samples 121, 80 and 33 times (respectively) the ASCP Guidelines (2001) permissible concentrations. In turn, content of Cr and Cd exceeded by five and six times those permissible limits. Moravia HM contents were also greater than those reported by Tesfai and Dresher (2009), for a landfill in Eritrea, North Africa. The extremely high HM content observed in Moravia samples is the result of more than a decade of inadequate disposal of diverse solid residues. Likewise, the high standar error of the mean (SEM) values reported, especially for Pb, Cr and Ni reflect the heterogeneous nature of the Moravia dump. The high pollution observed in Moravia evidences the need to undertake urgent pollution control measurements both at the Moravia dump and at nearby areas.

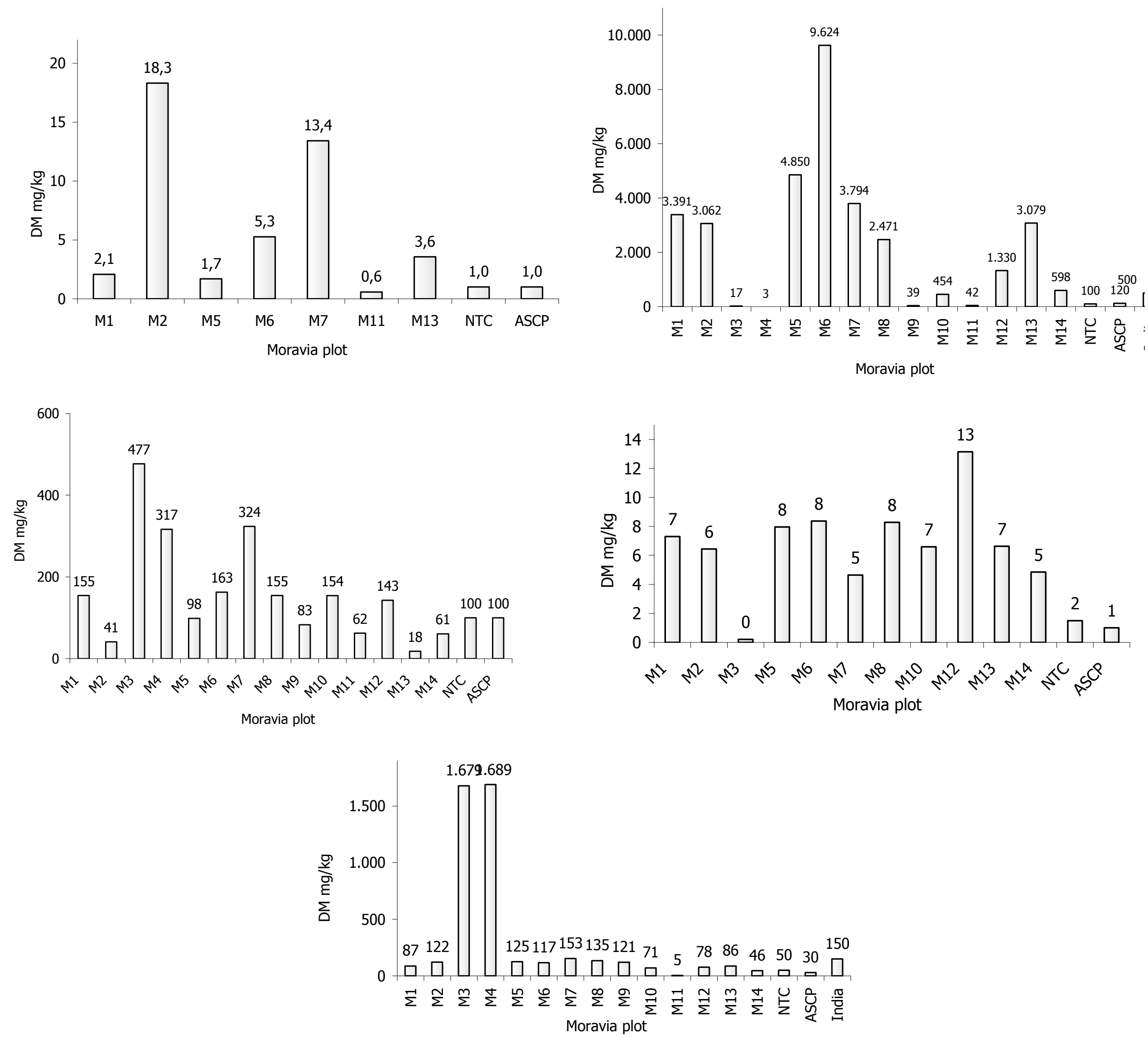

Figure 2. Total heavy metal content (mg/kg) in plot samples collected at the Moravia dump Medellín, Colombia.

Heavy metal content in plant species. Content (range and mean values) of HM in 28 samples from 13 plant species collected at the Moravia dump is shown in Table 5. For most species it was possible to collect two or three different samples, from the same number of plots. However, four of the 13 plant species analyzed could only be sampled from just one plot.

As shown by the content of HM found in plant tissues, plant species growing at Moravia absorbed HM to different extents, this being more noticeable in the case of Hg, Pb and Cr. In contrast, Cd and Ni were under the detectable limit in most plant samples, except for those from *R. communis* where a Cd concentration of 4.6 mg/kg was determined.

Table 5. Number of samples range and average for heavy metal concentration in plant tissues collected in Moravia dump. Medellín, Colombia.

Plant species	Descriptor	Hg	Pb	Cr	Cd	Ni
Alternanthera albotomentosa	n	3	3	3	3	3
	Range	0.24 - 0.80	2.8 - 3.2	68.4 - 86.3	<0.05	<0.250
	Average	0.5	2.3	74.4	__	__
Bidens pilosa	n	3	3	3	3	3
	Range	0.4 - 1.0	3.2 - 9.9	84.0 - 263.7	<0.05	<0.250
	Average	0.7	6.1	162.3	__	__
Cucurbita maxima	n	2	2	2	2	2
	Range	0 - 0.7	<0.125 - 3.1	<0.25 - 75.5	<0.05	<0.250
	Average	0.5	1.5	37.8	__	__
Emilia coccinea	n	3	3	3	3	3
	Range	0.4 - 1.0	0.3 - 45.7	61.3 - 100.8	<0.05	<0.250
	Average	0.9	27.1	77.3	__	__
Ipomoea cf trifida	n	2	2	2	2	2
	Range	0.4 - 0.9	2.0 - 12.4	2 - 30.4	<0.05	<0.250
	Average	0.6	11.4	55.3	__	__
Ipomoea nil	n	3	3	3	3	3
	Range	0.5 - 0.9	2.1 – 43.4	<0.25 - 12.0	<0.05	<0.250
	Average	0.6	17.6	4.0	__	__
Lepidium virginicum	n	3	3	3	3	3
	Range	0.2 - 0.9	34.0 - 123.7	29.6 - 80.4	<0.05	<0.250
	Average	0.6	66.6	48.8	__	__
Leucaena leucocephala	n	3	3	3	3	3
	Range	0.3	2.5 - 38.0	<0.25 - 3.0	<0.05	<0.250
	Average	0.3	15.4	23.2	__	__
Urochloa maxima	n	2	2	2	2	2
	Range	0.2 - 0.9	2.6 - 7.0	78.0 - 94.4	<0.05	<0.250
	Average	0.6	4.8	86.2	__	__
Pelargonium cf zonale		0.2	47.7	17.7	<0.05	<0.250
Ricinus communis		NA*	<0.125	12.3	4.6	<0.250
Carica papaya		0.4	<0.125	56.3	<0.05	<0.250
Commelina diffusa		0.3	0.3	72.8	<0.05	<0.250

Content of Hg (mg/kg) in all plant samples was lower than 1.0, with an average of 0.53 in all samples and with *B. pilosa, E. coccinea, I. nil* and *I. trifida* samples showing the highest concentrations.

Content of Pb varied greatly (from <0.125 to 123.7 mg/kg), with the highest concentration observed in *L. virginicum.* Likewise, Cr content varied greatly going from <0.25 to 263.7 mg/kg. The estimated SEM value for Cr content (10.38) was the highest among all HM and reflects the high variability in HM absorption among the plant species growing at the Moravia dump. This variability was exemplified in different samples from *L. virginicum* where the Pb content ranged from 34 to 123.7 mg/kg. Similarly, in *B. Pilosa*, Cr content varied from 84 to 263.7 mg/kg, with a SEM value of 53.2. Overall, HM content in plant tissues suggests the following order of plant HM absorption: Cr > Pb > Hg > Cd = Ni.

Heavy metal absorption in plants has been documented in several botanical families with some species identified as HM accumulators. Among these families, Asteraceae, Brassicaceae and Caryophyllaceae are commonly reported (Vara Prasad and De Oliveira, 2003).

Regarding HM content in their tissues, some of the plant species found in Moravia have been previously reported, whereas to our current knowledge, this is the first report for some species.

Bidens pilosa. This cosmopolitan annual herb native from tropical and Central America, has great reproductive potential and it is considered a major crop weed. It is used for medicinal purposes (Bhatt *et al.,* 2009). *B. pilosa* has been reported to absorb HM, especially Cd. A study reported that *B. pilosa* growing on a contaminated area had maximum HM contents (mg/kg) of 2.69 for Pb, 1.98 for Cr, 1.74 for Cd and 4.55 for Ni (Wu *et al*., 2009). In turn, when Wei and Zhou (2008), examined the ability of several plant species to absorb Cd, Cu, and Zn, *B. pilosa* exhibited great tolerance to Cd soil content and the accumulation of Cd in stems and leaves of the plant exceeded 100 mg/kg with soil Cd concentrations of 25, 50, or 100 mg/kg. In another study (Sun *et al*., 2009), *B. pilosa* was defined as a Cd hyperaccumulator as this species accumulated more than 100 mg/kg of Cd in its aerial tissues and showed characteristics of strong tolerance to adverse environments with fast growth and high biomass production.

In this study, *B. pilosa* was one of the most predominant plant species growing at Moravia dump, with maximum absorption (mg/kg) of 1.02 (Hg), 9.9 (Pb) and 263.7 (Cr), being the species showing the highest Hg and Cr contents. Contents of Pb and Cr were higher than those reported in the literature, probably due to the high levels of these HM in the Moravia dump. In the study, *B. pilosa* did not show Cd absorption. These differences could be related to the particular conditions in the Moravia dump, where a complex matrix of residues and contaminants could affect the bioavailability of HM, whereas in most literature reports, studies have been conducted under controlled conditions, usually adding Cd to a non contaminated soil.

***Lepidium virginicum*.** This annual herb is native to Central America and has been reported to be a colonizer on mine tailings, under an ongoing remediation process in Mexico (Ortega *et al*., 2009). To our knowledge, there are no specific reports on HM absorption by this species. However, a related species, *Lepidium sativum* has received attention for its characteristic arsenic accumulation. Smolińska y Cedzyńska (2007), conducted a laboratory study to examine the Hg phytoextraction capacity of *L. sativum* grown on soil contaminated with different amounts of Hg. In this study *L. sativum* was able to take up Hg from soil and accumulate it in plant tissues, according to the amount of Hg added to the soil. Maximum values of Hg in plant tissues were 1.68, 0.07 and 0.04 mg/kg in roots, stems and leaves of *L. sativum*, respectively. In our study, *L. virginicum* maximum contents of Hg, Pb and Cr were determined at 0.89, 123.7 and 36.3 mg/kg respectively. In fact, it was the species showing the highest content of Pb in the Moravia dump.

***Emilia coccinea*.** This species was reported as a weed growing on fields of the forage species *Tithonia diversifolia* (Asteraceae), in the rural region in Venezuela. In that study, *E. coccinea* had 49 mg/kg DM of Ni and there were no detectable contents of Cd or Pb. In this study, contents of Pb and Cr in the plant tissues of *E. coccinea* were 45.7 and 100.8 mg/kg, respectively (Olivares, 2009).

Panicum maximum (Syn: Urochloa maxima). This forage species known as guinea grass and native from the African tropical region is a fast growing grass that produces abundant biomass. Accumulation (mg/kg) of HM in tissues of *P. maximum* growing in the Ikeja Industrial Estate in Lagos, Nigeria, was reported to be 2.9, 2.3, 0.73 and 2.3 for Pb, Cr, Cd and Ni, respectively (Fakayode and Onianwa, 2002). A related grass species (deer tongue grass: *Panicum clandestinum*) is also widely distributed and commonly found on disturbed or contaminated sites and has been reported to contain between 10 and 20 mg/kg of Cd in leaves and stems, respectively when grown in soil contaminated by wastewater overflow and runoff from sludge piles (Sankaran and Ebbs, 2007). *Panicum maximum* was the most predominant species growing in Moravia dump, reaching almost 25% of the area covered by vegetation on the dump. The maximum HM content for this species growing at Moravia dump was determined at 94.4 mg/kg of Cr and 7.0 mg/kg of Pb, both quantities exceeding previous reports.

Leucaena leucocephala. This leguminous shrub native from Mexico is commonly used in agroforestry systems, due to its protein-rich foliage production for livestock. It has also been reported for its presence in several poor or contaminated soils, including landfills and places with high content of HM (Ma *et al*., 2007; Lins *et al.,* 2006). In the pot experiment conducted by Shanker *et al.,* (2006), when soil was artificially contaminated with different concentrations of Cr salts, *L. leucocephala* seedlings accumulated a maximum of 463.5 mg/kg of total Cr in roots and a maximum of 51.3 mg/kg of total Cr in shoots after one year of establishment. Despite this accumulation data, the authors concluded that the poor transfer of Cr from roots to shoots means that the prospects for using trees such as *L. leucocephala* are low and it would take long periods of time to remediate Cr contaminated soils. In our study, maximum contents of 0.35, 37.98 and 69.6 mg/kg for Hg, Pb and Cr were detected in samples of *L. leucocephala*.

***Alternanthera albotomentosa*.** This weed species has not been reported in relation to the accumulation of HM. However, an aquatic species from the same genus, *Alternanthera philoxeroides* (Mart.), has been reported to absorb HM (Ding *et al*., 2009). Evaluation of the Cd accumulation in leaves of *A. philoxeroides* reported Pb contents of 1838 and 990 mg/kg in roots and shoots respectively, determined in plants growing in a smelter area in China (Deng *et al.,* 2006). Maximum contents of HM in samples of *A. albotomentosa* growing in Moravia were determined at 0.8, 1.03 and 86.3 mg/kg for Hg, Pb and Cr, respectively.

***Ipomoea*.** This genus includes a wide variety of species including the sweet potato (I. batatas) and some of its species have been investigated for their phytoremediation potential. In a study conducted in a mine area contaminated with several heavy metals in Southern China, the species Ipomoea was reported to have maximum contents (mg/kg) of 12.84 and 176.95 of Cd and Pb, respectively (Liu *et al*., 2005). In this case, the contents of Pb increased from 12.76 to 53.32 mg/kg, when using 0.1 and 5 mM of EDTA (Ethylenediaminetetracetic acid) respectively. In Moravia we identified three Ipomoea different species, locally known as batatillas. Maximum contents (mg/kg) of HM among these three species were 0.92 (Hg), 43.4 (Pb) and 80.2 (Cr).

***Pelargonium*.** This ornamental genus has been evaluated for its Pb content (Arshad *et al*., 2008), where roots of different cultivars of *Pelargonium* sp. contained between 486 and 1467 mg/kg of Pb. Samples of *P. cf zonale* analyzed in Moravia, contained 47.7 mg/kg of Pb.

Using the plant biomass results and assuming this would be the same growth if these species were grown as a single crop, the ability of some of the plant species growing at Moravia to extract HM in a per hectare per annum basis was calculated. Given its greater biomass production, U. maxima could extract from Moravia more than 6 kg of Cr per ha per year. In turn, *L. virginicum* and *L. leucocephala* could extract 0.64 and 0.72 kg of Pb per ha per year. Clearly, a very long period of time would be needed for the decontamination of Moravia.

***Bioconcentration factor*.** The BCF is indicative of the efficiency with which a specific plant species accumulates heavy metals. Thus, it is considered that a species with a BCF greater than 1.0 has promising phytoremediation potential (Sun *et al*., 2009). According to BCF calculations (data not shown), the absorption of Pb and Cr accumulation varied among species and within the same plant species collected in different plots. The highest Cr BCF values were observed in B. pilosa (1.68) and *E. coccinea* (1.13), whereas the highest Pb BCF values were observed in *E. coccinea* (1.18) and *L. virginicum* (1.09). Based on BCF values, the plant species *B. pilosa, E. coccinea, A. albotomentosa* and *I. trifida* absorb Cr to a greater extent compared to other plant species in Moravia dump.

It is important to say that some species growing in the Moravia dump, are the result of the cultivation conducted by Moravia dump inhabitants. At the sampling time in this study, some species such as tomato (*Lycopersicon esculentum*), mango (*Mangifera indica*), orange (*Citrus* sp.), banana (*Musa paradisiaca*) and *Cucurbita maxima* were growing there, and were previously planted by the inhabitants, with the purpose of complement their diet with the fruits of these bearing species. The content of Pb in the edible species *C. maxima* (3.05 mg/kg) or the content of Cr in *C. papaya* (56.3 mg/kg) and *C. maxima* (75.5 mg/kg), is preoccupying since it exceeds by far the permissible limits established by the Codex Alimentarius Commission (2006), where maximum contents (mg/kg) allowed in vegetable foods are 0.1 (Pb) and 2.6 (Cr).

Overall, the HM content in Moravia dump plant samples confirm that HM are being absorbed by plants and there could exist the risk that HM enter the food web.

Likewise, our observations of HM content in RM samples and plant tissues from Moravia dump suggest that *B. pilosa, A. albotomentosa, L. virginicum* y *U. maxima* possess great ability to thrive under the conditions of the site.

Phytoextraction is defined as the use of plants to extract contaminants from soils. In a given plant species, the phytoremediation capacity is directly related to contaminant bioavailability. Such bioavailability is affected by physical and chemical soil properties, especially by pH and organic matter content. It is generally accepted that low pH values increase metal bioavailability, while high organic matter contents have been associated to retention and reduced metal bioavailability (Pilon-Smits, 2005; Antoniadis *et al.,* 2008; Quenea *et al.,* 2009). The term hyperaccumulator refers to plant species that can accumulate more than 1000 mg/kg of Pb or Ni, or more than 100 mg/kg of Cd in their aerial tissues. Therefore hyperaccumulators are highly desired in decontamination process by means of phytoextraction.

In the case of the Moravia dump, and comparing the overall HM content in RM and plant tissues, as well as some FBC values, it appears that the HM in the RM from Moravia are of low bioavailability. This could be due to the pH (between 7 and 7.6) and the high organic matter content of Moravia RM, which could lead to low HM bioavailability. In our study, only *L. virginicum* and *B. pilosa* had a BCF > 1, but this was not observed in all the plots. Despite the low BCF, our data validate any future attempts to evaluate the potential of *B. pilosa*, *L. virginicum, U. maxima* and *E. coccinea* as suitable plants for the revegetation process in Moravia.

In the case of the Moravia dump, the revegetation process necessary for its rehabilitation must be man influenced. According to Prach and Pyšek (2001), restoration projects may rely on spontaneous succession, except where extreme toxic substrates are present. In this study, the extremely high HM content observed, both among RM and plant samples, suggest the necessity to design and conduct a restoration process in the Moravia dump, which includes a man induced revegetation process. Factors inherent to the geological stability of Moravia dump RM, should be taken into account if the establishment of trees is desired. Finally, the establishment and growth of edible and medicinal species, should be avoided.

CONCLUSIONS

The Moravia dump area, former receptor of the municipal wastes from the city of Medellín, provides suitable conditions for the growth of numerous plant species, as shown by the number of plant species identified there. One of the reasons for this is the high amount of organic residues deposited there, which could have provided the nutrients required for plant growth. It may be expected that the floristic composition reported in this study will change in the near future, as a consequence of the spontaneous revegetation process. For example, it is possible that trees and shrubs should at some point become the dominant stratum at Moravia dump, condition that can be of geotechnical concern. In consequence, the revegetation process, should be controlled and continuously monitored.

It is evident that the Moravia dump is heavily contaminated with HM and that immediate action should be taken in order to control and reduce pollution *in situ* as well as, pollution of nearby areas. As sealing a former dump is not a guarantee that the contamination problem is solved (Lopes *et al.,* 2006), those actions should be centered on controlling superficial water movement, preventing erosion and controlling the generation and migration of lixiviates. The use of some of the plant species reported in this study would be a great contribution towards this goal.

The content of HM in plant tissues is an evidence of the present risk that Moravia dump poses to its inhabitants, human population included. Municipal authorities should pay special attention to avoid the planting and harvesting of edible and medicinal plant species.

With regard to the high variability in HM content in RM and plant tissue samples, it must be remembered that the sampling methodology used in this study could affect to some extent the observed results.

Therefore, we suggest a future evaluation, under controlled or semi controlled conditions, in which the HM absorption could be evaluated throughout different plant development stages, in order to increase the accuracy of the results obtained in this study. We also suggest future investigation regarding the accumulation of HM in the different plant organs, in order to assess the phytoextraction and phytostabilization potential of the different species. Furthermore, the plant diversity the found in the Moravia dump, should be considered at the moment of selecting plant species for the revegetation of this place. Finally, it would be ideal to conduct a study of HM speciation, to determine the fraction (exchangeable, carbonate, Fe-Mn oxides, organic, or residual; Tessier *et al.,* 1979) in which HM predominate in the Moravia dump RM.

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