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Evaluating the role of vegetation on the transport of contaminants associated with a mine tailing using the Phyto-DSS

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ABSTRACT

We identified contaminants associated with the Cata mine tailing depot located in the outskirts of the city of Guanajuato, Mexico. We also investigated strategies for their phytomanagement. Silver and antimony were present at 39 and 31 mg kg^{-1}, respectively, some twofold higher than the Dutch Intervention Values. Total and extractable boron (B) occurred at concentrations of 301 and 6.3 mg L^{-1}, respectively. Concentrations of B in soil solution above 1.9 mg L^{-1} have been shown to be toxic to plants. Plant growth may also be inhibited by the low concentrations of extractable plant nutrients. Analysis of the aerial portions of *Aloe vera* (L. Burm.f.) revealed that this plant accumulates negligible concentrations of the identified contaminants. Calculations using a whole system model (Phyto-DSS) showed that establishing a crop of *A. vera* would have little effect on the drainage or leaching from the site. However, this plant would reduce wind and water erosion and potentially produce valuable cosmetic products. In contrast, crops of poplar, a species that is tolerant to high soil B concentrations, would mitigate leaching from this site. Alternate rows of trees could be periodically harvested and be used for timber or bioenergy.

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1. Introduction

Historically, mining activities have resulted in the production of large volumes of tailings that detrimentally affect nearby zones due to wind and water transportation of contaminated material [1,2]. Tailings may have properties that make them unsuitable for plant growth. These include high concentrations of metals, low concentrations of plant nutrients and unusual pH values [3–5]. Commonly, mine tailings have a low water retention capacity [6], high electrical conductivity and steep slopes [7].

The Cata silver and gold mine has been active since the 18th century. From 1944 to 1948, some 320,000 t of tailings were deposited at a site that has become known as the Cata tailings on the outskirts of the town of Guanajuato and above the Guanajuato River. The site has an inclination of 18°. In the 60 years following the tailings deposition, dust has affected nearby houses and locals have complained of respiratory problems. During periods of high rainfall, tailings material is usually washed into a small waterway that flows into the Guanajuato river which flows into the La Purisima dam that provides water to irrigate 4500 ha in the region that receives just 650 mm of rainfall annually [8,9]. Therefore, contaminants in the mine tailings may be transferred to agricultural soils and crops.

In the 60 years since the tailings were deposited, plants have sporadically colonised the tailings. The most important with respect to biomass and abundance is *Aloe vera* (L. Burm.f.). This plant is native to Africa. However, nowadays it is widely spread on arid Mexican soils and is used as a medicinal plant.

Apart from anecdotal reports of respiratory complaints from the local population, the environmental and human health risks associated with these tailings are unknown. There is no available information on the chemical composition or physical properties of the tailings. Observation indicates that the tailings are mobile, so any contaminants contained therein may pose a threat to human health or ecosystem functioning.

We hypothesise that these tailings contain elevated concentrations of heavy metals, since other mine tailings in the area contain elevated concentrations of As (168 mg kg^{-1}), Zn (1129 mg kg^{-1}), Pb (308 mg kg^{-1}), and Cu (429 mg kg^{-1}) [10,11].

Establishment of continuous vegetation cover on the Cata mine tailings could reduce environmental and human health risks [12]. The goal of such a phytomanagement programme would be to minimise the environmental risk associated with the tailings, while

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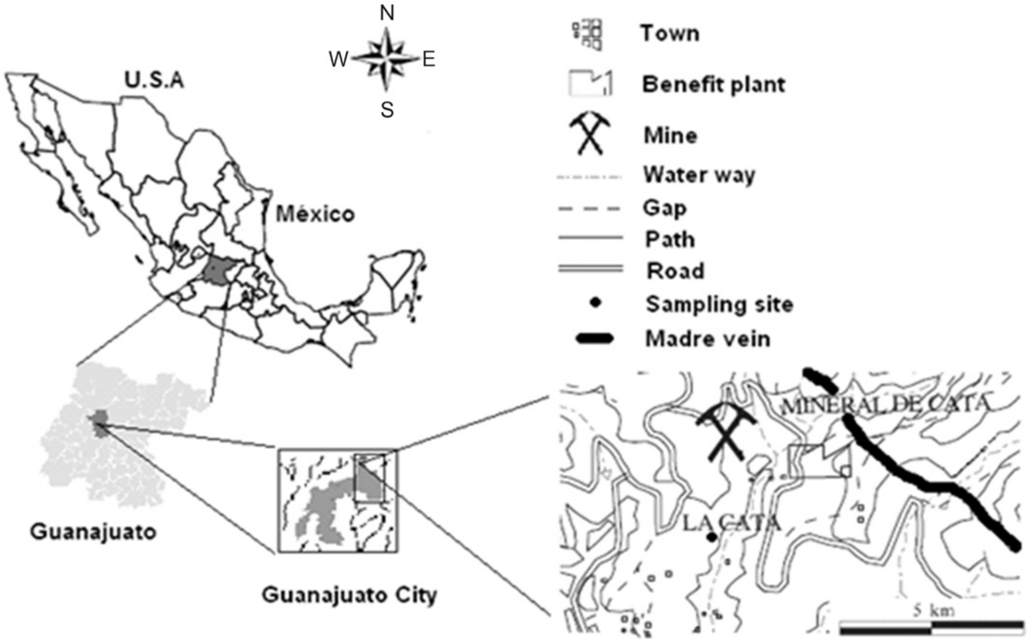

Fig. 1. Location of La Cata mine tailings in Guanajuato, México.

producing valuable biomass or enhancing the aesthetic or ecological value of the site. Evapotranspiration would reduce the water flux through the site and therefore reduce the leaching of any toxic heavy metals that may be present [13]. Establishment of vegetation would require the identification of regional and climatic specific plants which show low metal uptake in shoots and determination of the minimum requirements in amendments (compost, fertilizer, irrigation) required for plant growth [14].

We also hypothesise that *A. vera* would be a suitable candidate for revegetation, since it has naturally colonised part of the tailings. The objectives of this research were to determine the chemical and physical characteristics of the tailings as well as elemental uptake by *A. vera* to determine the key factors limiting the establishment of vegetation and identify any elements that may pose an environmental or human health risk. Secondly, using these data to parameterise a whole-system model, we aimed to determine the effect of revegetation on contaminant fluxes in the Cata mine tailings by using the Phyto-DSS (Phyto Decission Support System).

2. Experimental

2.1. Sampling procedure

Between June and August of 2008, seven sites were selected for sampling on the Cata tailings (Fig. 1). At each site, 5 sub-samples of the tailings were sampled in a one meter radius. After removing surface litter, approximately 2 kg tailings were taken from a depth of 0–30 cm and mixed [15]. The tailings were air-dried, sieved to <2 mm and stored for analysis. We sampled roots and leaves of *A. vera* plants from three of the five sub-sampling locations per site. Plant samples were first washed with running tap water to remove debris, later with distilled water and finally with 0.01 M HNO_3. Plants were separated into roots and stems and oven-dried at 70 °C for 72 h. After drying, samples were ground using a mortar and pestle. For elemental analysis, approximately 0.2 g of plant tissue were microwave-oven digested using 3 mL plasma pure HNO_3 [16]. Soils were digested in a similar manner using *aqua regia*.

2.2. Determination of extractable elements

Extractable element concentrations in soils were determined using water (0.4 g soil, 10 mL water) DTPA (1 g soil, 2 mL DTPA 0.005 M) and $CaCl_2$ (1 g soil, 10 mL $CaCl_2$ 0.01 M), [17]. The concentration of elements in soil solution, C (mg L^{-1}), was calculated from the concentration in the water extract W (mg kg^{-1}) using the following formula [1]:

$$C = W\rho F \quad (1)$$

where W is the element concentration in the water extract (mg kg^{-1}); F is the maximum content water in the soil (L L^{-1}); ρ is the bulk density of the soil (kg L^{-1}).

After centrifugation and filtration, concentrations of As, Ni, Pb, Zn, Cu, Cr, Ag, Cd, Mo, Se, B, Mn, S, Si, Fe, Ca, Mg were determined using inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). For quality assurance reference materials from the US National Institute of Standards and Technology were also analysed. The recoveries of the aforementioned elements were (96% B, 98% Cd, 94% Mn, 98% Fe, 88% Cu in plants).

2.3. X-ray fluorescence analyses

Soil samples were ground using a Retsch RS1 grinder with a tungsten carbide ball and ring. Plant samples were ground using a Retsch ZM200 titanium mill. Ground material (4 g) was mixed with 0.9 g of wax and pressed into tablets under a pressure of 15 t. The total element concentrations (Mg, Si, S, Ca, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sb, Hg) of the tablets were determined using a Spectro X-lab 2000 X-ray fluorescence (XRF) spectrometer. For quality assurance, we analysed 4 Wageningen soil standards, 958, 998, 989, and 951 as well as a certified plant reference material (poplar leaves NCS DC73350, China National Analysis Center for Iron and Steel, Beijing, China). The average recoveries for soils were: Ca 113%, Cu 117%, Fe 106%, Pb 115%, Mg 89%, Mn 112%, Ni 125%, Sb 121%, and Zn 101%. For the plant standard, the recoveries were: Ca 96%, Cu 101%, Fe 98%, Mg 67%, Mn 126%, Ni 89%, and Zn 99%. In the plant reference, Pb and Sb were below the detection limits of our method for plant samples (<2 mg kg^{-1}).

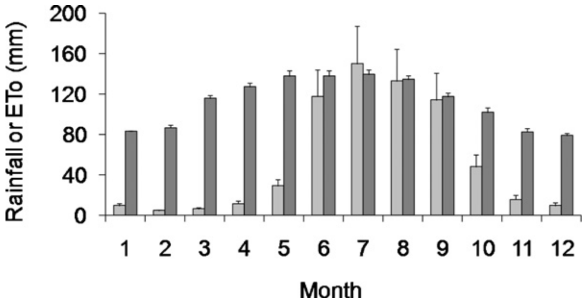

Fig. 2. Average monthly rainfall ☐ and evapotranspiration ■ in Guanajuato, Mexico. Error bars represent the standard deviation of the mean.

2.4. Determination of soil agronomic properties

The soil was sand silt clay [18] containing 0.59% organic matter [19]. The field capacity and permanent wilting point were determined by plate and membrane technical, the P content by the Olsen technique [20]. The NO_3–N was determined using cadmium column [21]. Extractable K and cationic exchange capacity (CEC) were measured using ammonium acetate [22]. Soil pH was measured at a soil: solution ratio of 1:2 (soil: deionised water) and electrical conductivity determined using a conductivity meter [23]. All values of soil properties are shown in Table 2.

2.5. Statistical treatment of data

MINITAB (Minitab Inc., Pennsylvania State University, University Park, Pennsylvania) was used for ANOVA (at the 5% level) and correlation analyses. Data that were log-normally distributed were log-transformed for statistical analyses. For log-normal data, we report geometric means and standard deviation ranges rather than means and standard deviations. With log-normal data, the geometric mean is a better measure of central tendency than the arithmetic mean. Use of geometric means reduces distortions caused by a few anomalous values and produces a value of better centrality.

2.6. Modelling the effect of vegetation regime on drainage and contaminant leaching

Long-term monthly averages for rainfall and potential evapotranspiration were obtained from Centro de Ciencias Atmosféricas de la Universidad de Guanajuato and Comisión Nacional del Agua [8,9]. Daily values were simulated for a 20-year period (2010–2030) using a climate simulator [24]. These data are shown in Fig. 2.

Simulations were run using the Phyto-DSS [13] to calculate the leaching from the mine tailings without vegetation and with hypothetical crops of *A. vera* (L.) and poplar species. Plant metal uptake was calculated using Eq. (2):

$$M(t) = \int_0^{z_R} \int_0^t R(t', z)T(t')C(t'z)\phi(C(t'z))dt\,dz \qquad (2)$$

where M is plant metal uptake in the time interval (0, t; days). R is the fraction of the total root water uptake at depth z (m), T is the transpiration rate ($\mathrm{L\,day^{-1}}$), C is the TE concentration ($\mathrm{mg\,L^{-1}}$) in the soil solution, and ϕ is the root absorption factor. Table 1 shows the plant parameters used in the Phyto-DSS.

The movement of water and solutes in the substrate is calculated using a tipping-bucket approach similar to that described in [25]. These calculations used soil parameters shown in Table 1.

Table 1
Parameters used in the Phyto-DSS for *Aloe vera* and *Populus* spp.

	Aloe vera	*Populus*[a]
Root depth (m)	0.8[b]	1
Water use efficiency ($\mathrm{kg\,m^{-3}}$)	18[c]	2
Kc (max)	0.20[b]	1.00
Root absorption factor for boron	0.15	0.20

[a] [45].
[b] [46].
[c] [47].

Table 2
Physical and chemical properties of tailings from the Cata mine.

	Cata tailings	Normal range
pH	8.13 (<0.01)	5–8.5[a]
Organic matter (%)	0.59 (0.02)	1–10[a]
Electrical conductivity ($\mathrm{dS\,m^{-1}}$)	0.931 (0.01)	<2[a]
Cation exchange capacity (Cmol(+)$\mathrm{kg^{-1}}$)	19.60 (0.15)	5–40[a]
P ($\mathrm{mg\,kg^{-1}}$)–Olsen	1.68 (<0.01)	10–20[a]
N–NO_3 ($\mathrm{mg\,kg^{-1}}$)	2.93 (0.03)	10–30[b]
K(ammonium acetate) ($\mathrm{mg\,kg^{-1}}$)	39 (0.4)	90–130[c]
Texture		
Sand (%)	63 (1)	–
Silt (%)	26 (<0.01)	–
Clay (%)	11 (1)	–
Saturation point (%)	41 (0.6)	–
Field capacity (%)	31 (0.4)	–
Permanent wilting point (%)	20.5 (0.2)	–
Density ($\mathrm{gr\,cm^{-3}}$)	1.15 (0.015)	–
Moisture (%)	20.5 (0.02)	–

Data in brackets are standards deviation.
[a] [15].
[b] [48].
[c] [49].

3. Results and discussion

3.1. Fertility of the Cata mine tailings

Table 2 gives some chemical and physical soil properties affecting the potential of the Cata mine tailings for plant growth. The soil is moderately alkaline, indicating that excessive leaching or plant uptake of cationic trace elements is unlikely. However, anion-forming trace elements may be more mobile at these pH values. The electrical conductivity of the tailings indicates that salinity is unlikely to negatively affect plant growth at this site.

Concentrations of organic matter, nitrate-N and Olsen-P and exchangeable K are well below ranges that occur in fertile soils. This indicates that plant growth on this site is probably reduced due to the lack of nutrients.

The optimal available water content is in the range of 60–90% at field capacity [26]; however, the maximum available water content of these soils was low (10%) indicating that any plants used for revegetation should necessarily be drought tolerant.

3.2. Elemental contaminants in the Cata mine tailings

Table 3 shows the total and extractable concentrations of potential elemental contaminants in the Cata mine tailings as well as the Dutch Intervention Values, which are internationally recognised standards for assessing soil and groundwater quality [27]. Total concentrations of Ag and Sb exceed the respective Intervention Values for these elements in soils, indicating that they may pose a danger to humans or ecosystems. Although below detection limits in the extracts, the alkali nature of the tailings may favour the mobility of Sb, which is usually present in the environment as the oxy-anion $Sb(OH)_6{}^-$ [28].

Table 3
Total concentration (mg kg^{-1}) of main trace elements in the Cata mine tailings in various extracts. "Total" represents a pseudo-total obtained via an *aqua regia* digest. Values represent the geometric mean and standard deviation ranges in brackets unless otherwise indicated.

	Concentration in soil solution (mg L^{-1})	Water (mg kg^{-1})	$CaCl_2$ (0.01 M) (mg kg^{-1})	DTPA (mg kg^{-1})	Total (mg kg^{-1})	DIV (mg kg^{-1})
Ag	<0.01	<0.01	<0.005	0.003 (0.03)[a]	39 (32–47)	15
Cr	0.098 (0.049)[a]	0.04 (0.02)[a]	0.0007 (0.00024–0.002)	0.009 (0.007–0.01)	19 (16–21)	380
Cu	0.78 (0.54–1.2)	0.32 (0.22–0.48)	0.06 (0.04–0.09)	1.7 (1–3)	25 (15–42)	190
Zn	0.63 (0.27)[a]	0.26 (0.11)[a]	0.3 (0.2–0.4)	1.9 (1.4–2.5)	46 (34–63)	720
Pb	0.49 (0.24–0.73)	0.2 (0.1–0.3)	0.0058 (0.002–0.014)	1.43 (0.52–3.95)	10 (5–20)	530
Ni	0.049 (0.024)[a]	0.02 (0.01)[a]	0.065 (0.06–0.07)	0.12 (0.02)[a]	9 (7–11)	210
As	0.27 (0.19–0.39)	0.11 (0.08–0.16)	0.79 (0.03)[a]	0.39 (0.37–0.42)	7 (5–9)	55
Cd	<0.007	<0.007	0.006 (0.004–0.008)	0.04 (0.03–0.06)	0.17 (0.13–0.22)	12
Mo	0.073 (0.024–0.19)	0.03 (0.01–0.08)	<0.008	<0.007	1.1 (1.03–1.1)	200
Se	0.17 (0.073)[a]	0.07 (0.03)[a]	0.54 (0.51–0.59)	0.53 (0.04)[a]	2.3 (0,4)[a]	100
Hg	ND	ND	<0.02	0.46 (0.003)[a]	2 (1.5–2.5)	10
Sb	ND	ND	<0.02	<0.02	31 (4)[a]	15
B	6.3 (0.49)[a]	2.6 (0.2)[a]	6.3 (0.6)[a]	5.7 (1)[a]	301 (34)[a]	–
Mn	5.8 (2.3)[a]	2.4 (0.94)[a]	2.7 (1.9–3.9)	23 (19–29)	751 (716–788)	–
S	17.3 (2–148)	7.1 (0.8–60.6)	109 (52–230)	35 (13–94)	507 (345–745)	–
Si	349 (159)[a]	143 (65)[a]	15 (2)[a]	6.5 (1.3)[a]	151 (87–260)	–
Fe	98 (45)[a]	40.2 (18.4)[a]	0.37 (0.09)[a]	9.4 (7.9–11.2)	9675 (7748–12082)	–
Ca	703 (442–1117)	288 (181–458)	3953 (3751–4166)	881 (725–1071)	22369 (19823–25242)	–
Mg	85 (68–105)	35 (28–43)	41 (9)[a]	23 (18–31)	6954 (6111–7915)	–

Dutch Intervention values (DIV). Not determined (ND).

[a] Arithmetic mean and standard deviation.

Table 4
Elemental concentrations (mg kg^{-1} dry matter) in seven samples of the Cata tailings and three samples of *Aloe vera* from the Cata mine tailings. Values in brackets are standard deviations. The MTIs for Sb and Hg are 0.86 and 2 ug kg^{-1} bodymass day^{-1}. The TDI for silver was taken at 20 ug per person per day.

Element	Concentration (mg kg^{-1})	Maximum intake (g) (15 kg child)	Maximum intake (g) (70 kg adult)
Tailings			
Ag	39 (32–47)	0.5	
Sb	31 (4)[a]	0.42	1.9
Hg	2 (1.5–2.5)	15	70
Aloe vera			
Ag	1 (0.6)[a]	20	
Sb	<0.3–0.7	18	86
Hg	<0.4	>75	>350

MTIs references: Ag [29], Sb [50], Hg [51].

[a] Arithmetic mean and standard deviation.

Inhalation or consumption of dust particles may result in the ingestion of dangerous levels of some contaminants. Table 4 shows the amount of tailings that a child (15 kg) and adult (70 kg) would need to consume to exceed the Maximum Tolerable Intakes for the elements identified as contaminants in Table 4. Consumption of just 0.4 g of tailings per day would result in Sb intake above the MTIs of 0.86 μg kg^{-1} body mass day^{-1}. This level of dust ingestion would also result in a total Ag intake of 20 μg day^{-1}. In the stomach, where the low pH is due to the presence of hydrochloric acid, silver is precipitated as silver chloride. The low solubility of silver in the presence of chloride is consistent with its low bioavailability since oral administration of radio-labelled silver to mice, rats, monkeys and dogs has shown that 90% or more of oral doses were not absorbed [29].

Inhalation of the tailings may also result in irritation of the respiratory tract due to the size and shape of the dust particles, which were not measured in this study. Data from NIOSH and OSHA [30,31] indicate that the inhalation of particles from mining tailings that are <5 μ in diameter containing particles of silica (SiO_2) can cause respiratory diseases such as silicosis and fibrosis which are progressive. Non-occupational exposure from dust may affect people living near mine tailings [32]. The physical characteristics of dust particles from the Cata mine tailings should be the focus of future research.

The total concentration of B is in the range found in soils where plant growth is inhibited by B toxicity and the concentration of B in soil solution (1.9 mg L^{-1}) will result in toxicity in all but the most tolerant plants [33–35]. It is likely that vegetation is being inhibited by B toxicity in addition to nutrient deficiencies.

The high concentrations of B in soil solution indicated that leaching from the Cata mine tailings may result in B concentrations in receiving waters above the threshold for B in drinking water (1.3 mg L^{-1}) or the threshold for ecological effects in aquatic systems (0.37 mg L^{-1}) [36]. Sources about data on B aquatic organisms toxicity reveal that the most sensitive species in laboratory tests was determined to be the embryo–larval rainbow with a lowest observed effect concentration of 0.1 mg L^{-1} [37], however subsequent studies suggested B risk to freshwater environments effect concentrations between 0.75 and 1.0 mg L^{-1} [38,39], though some microoganisms have toxicity thresholds between 0.16 and 0.28 mg L^{-1} [40].

3.3. *Reducing the negative environmental effects of the Cata mine tailings*

Our results indicated that the primary risks associated with the Cata mine tailings are the transport of Sb and Ag offsite via dust, which may be inhaled or consumed, and by the leaching of B into receiving water to produce concentrations sufficient to damage aquatic ecosystems. Establishing a total vegetation cover on the site could eliminate wind-borne erosion and reduce leaching. However, plant growth is likely inhibited by low concentrations of plant nutrients and high concentrations of B.

The fertility of the mine tailings could be augmented by fertilisation. The addition of compost with a low C:N ratio may make the most suitable soil amendment as this would improve soil structure by adding organic matter to the soil. With this, wind-borne erosion is reduced and the water holding capacity is increased providing

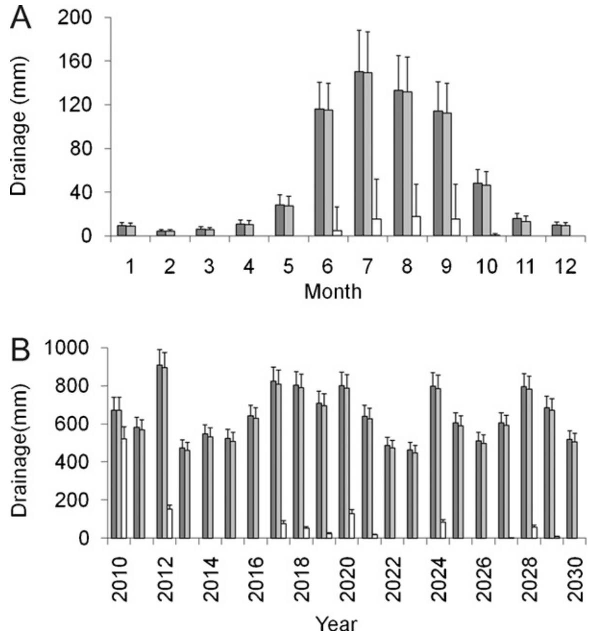

Fig. 3. Average monthly (A) and annual (B) drainage from the Cata mine tailings without vegetation ■, with a crop of *Aloe vera* ▨, and under poplar trees □ during a 20 year period. Drainage was calculated on a daily basis. Error bars represent the standard error of the mean.

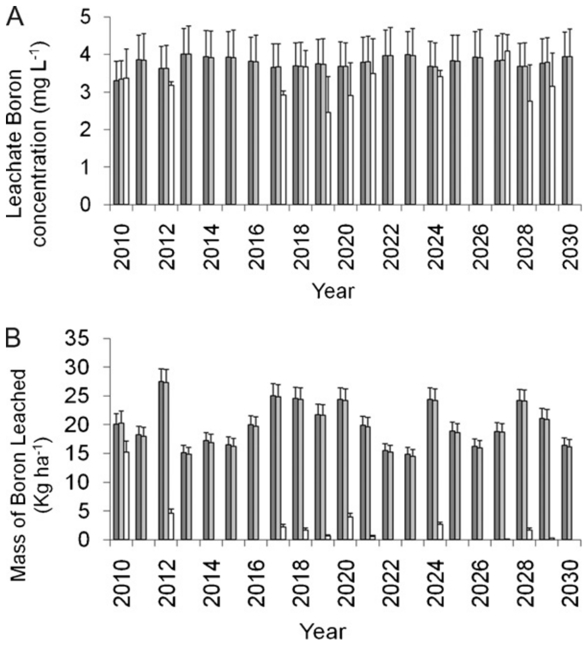

Fig. 4. Calculations of average annual leachate boron concentrations (A) and the total amount of boron leached from the Cata mine tailings without vegetation ■, with a crop of *Aloe vera* ▨, and under poplar trees □, during a 20 year period. Leaching was calculated on a daily basis. Error bars represent the standard error of the mean.

plant-available N and P through oxidation, [41]. Sewage sludge (or biosolids) may be a suitable low-cost organic amendment that contains high concentrations of plant nutrients, particularly N and P. The elevated concentrations of some heavy metals in the sludge are less important as the site is in any case contaminated.

Candidates for revegetation must necessarily tolerate the local conditions. Ideally, they should stabilise the soil surface and preferably produce some form of valuable biomass. *A. vera* is an obvious candidate since it is growing spontaneously on the tailings, indicating that it tolerates local conditions. Species of *Populus* are widely used for phytoremediation [42] because various clones are tolerant to a wide range of environmental conditions. Poplar establishes rapidly from cuttings and the biomass can be removed via coppicing without the need for replanting. Poplar is tolerant to high B concentrations [24] and some species, such as *Populus tristis* are tolerant to periods of drought [43], which occur during November–April in Guanajuato (Fig. 1).

We calculated the effects of a crop of *A. vera* and *Populus* species on the drainage from the site as well as the drainage from the site without vegetation (Fig. 3). In all scenarios, most drainage occurs from June to September (Fig. 3A), coinciding with the high rainfall during this period (Fig. 2). There was no significant difference ($P = 0.75$ NS) in drainage between the bare site and the site vegetated in *A. vera*. This is because of the relatively low crop coefficient of *A. vera* (Table 1). In contrast to *A. vera*, planting the site with poplars would cause a significant decrease ($P = 0.00\,S^{**}$) and result in just 8% of the drainage that would occur from the bare site or under *A. vera*.

Calculations of the mass of B as well as the concentration of B that would leach from the mine tailings with a cover of *A. vera*, *Populus spp*. and with no vegetation are shown in Fig. 4. Over the 20-year simulation, a correlation analysis revealed that there was no significant change in either the concentration of B in the leachate ($r = 0.262$ $P = 0.25$ NS) or the total mass of B ($r = -0.08$ $P = 0.726$) leaching from the pile on a yearly average basis. This is because the mass of B leached from the tailings is negligible compared to the total concentration present and variations caused by annual differences in rainfall are more important. Concentrations of Ag, Hg and Sb were below detection limits in the $CaCl_2$ extractant (<0.02 mg kg^{-1}). We have therefore calculated a "worst case" scenario in the mass and concentrations of these elements that may leach from the pile on an annual basis (Table 5).

For all the elements calculated, planting the site in *A. vera* would have no significant effect on the concentrations ($P = 0.93$ NS) or total masses ($P = 0.86$ NS) of these elements that are leached. This is because *A. vera* would cause no significant reduction in the volume of draining from the site (Fig. 3A and B) and because of the relatively low uptake of these contaminants (Table 4). Leaves of *A. vera* could be harvested to provide skin products and other types of snake oils that could be sold and thus provide an economic return from the site. Analysis of *A. vera* leaves revealed that these plants do not accumulate sufficient quantities of the soil contaminants to pose a human health risk. For example, the obtained information in the leaves for mercury and antimony show concentrations <0.4 and <0.3–0.7 mg kg^{-1}, respectively, while heavy metals concentrations in cosmetic products are seen to be technically avoidable when they exceed 3 and 5 mg kg^{-1}, respectively [44].

In contrast to *A. vera*, poplars would cause a significant decrease in the mass ($P = 0.00\,S^{**}$) and concentration ($P = 0.00\,S^{**}$), of these B leaching from the tailings. This might result from the reduction in drainage caused by the high evapotranspiration from a crop of poplars (Fig. 3A and B) as well as by the hyperaccumulation of B in the leaves of poplar. Using parameters from [45], we would expect the leaves of poplar at this site to contain some 900 mg kg^{-1} B on a dry matter basis. Calculations were performed with poplar, since previous work [45] has shown that this is extraordinarily tolerant to boron, while Eucalyptus succumbed to boron concentrations just one fifth of the values found in the present study. In addition, the Phyto-DSS requires parameterisation with values for water use efficiency, maximum crop coefficient, and root adsorption factors for various elements. These data is available for poplar [45] but not for others such as *Leucaena* and *Robinia*. Therefore, we cannot yet make accurate calculations of growth, transpiration and boron uptake by these plants.

Table 5
Calculations of the annual mass (M) (kg ha^{-1}) and concentration (C) (mg L^{-1}) of contaminant leaching from the Cata mine tailings mean annual kg and mg L^{-1}, respectively. The mass and concentration values are the mean annual when there was contaminant leaching. Values represent the geometric mean and standard deviation ranges in brackets unless otherwise indicated.

	Without crop		*Aloe vera*		*Poplar*	
	M	*C*	*M*	*C*	*M*	*C*
B	20.2 (4)[a]	3.8 (0.2)[a]	19.8 (16–24)	3.9 (0.2)[a]	1.6 (0.3–6.4)	3.6 (0.4)[a]
Ag	<0.018	<0.01	<0.017	<0.01	<0.001	<0.01
Sb	<0.072	<0.014	<0.071	<0.014	<0.006	<0.013
Hg	<0.072	<0.013	<0.071	<0.014	<0.006	<0.011

[a] Arithmetic mean and standard deviation.

Unless the trees were harvested, B would be returned to the tailings annually when the leaves are abscised. Boron could be removed via partially coppicing the trees to produce non-food crops such as timber or bioenergy.

4. Conclusions

Dust from the Cata mine tailings may present a human health risk in nearby areas due to the concentrations of Sb and Ag that are above Dutch Intervention Values for soils. The dust may also have physical properties that have detrimental effects on health, a topic worthy of further investigation. Low concentrations of plant macronutrients and excessive concentrations of B may inhibit plant growth and result in high concentrations of B leaching from the site and damaging aquatic systems. Dust could be greatly reduced or eliminated by revegetating the site with B-tolerant species such as *A. vera* or poplar. Revegetation would require soil conditioners to improve the tailings nutrient status and water retention properties. *A. vera* would have little effect on B leaching; however, poplar would significantly reduce both the volume of drainage from the site and the concentration of B in the drainage water. Testing is required to determine which poplar species or clone (if any) would thrive on these mine tailings.

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