Multidisciplinary field research in Kabwe, Zambia, towards better understanding of lead contamination of the city - A short report from a field survey

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Abstract: Heavy metal contamination is a serious issue in many post-mining area around the world. Kabwe city, Zambia, is known as one of the most polluted cities in the world and high lead (Pb) levels that have been reported in soils, plants, animals and human bloods. Multidisciplinary approaches are critically needed to understand the current situation and to remediate the polluted area. In the current research, we performed a large scale preliminary field survey to understand the current situation in Kabwe and to plan future mitigation approaches. Mainly, three aspects were observed; 1) plant communities during the dry season in Kabwe city, 2) spectral images of the land surfaces in various locations in Kabwe and 3) lead concentrations in soils and water. Overall, >15 different plant species were observed and many of them maintained their green color even during the dry season. Some tree species, for example, *Caesalpiniaceae* and *Fabaceae* families may be utilized as phytostabilization approaches although their impacts on the soil lead mobility have to be further studied. For the spectral images, we used a handmade portable spectrometer and our obtained spectral images showed typical curves observed from soils. These data may be used to understand the distribution of different soil types in this area, using aboveground images such as satellite images. For Pb concentrations in soils, extremely high total Pb levels (>1,000 ppm) was observed only within 2 km from the mining site. There was a weak but a positive correlation between the total and soluble lead thus further study should also focus on the mobility of Pb from soils to plant ecosystems.

Keywords: Pb, spectral images, plant community structures

1. Introduction

There have been a large number of studies performed to evaluate the status of heavy metal contamination in Kabwe, Zambia. Due to the history of mining of lead (Pb) and zinc (Zn), it was reported that soils were contaminated with not only by Pb and Zn but also by copper (Cu) and cadmium (Cd) (Nwankwo & Elinder, 1979; Tembo, Sichilongo, & Cernak, 2006). The contamination of the soils in the area resulted in the extensive heavy metal pollution of livestock (cattle) (Yabe et al., 2011), chicken, vegetables, and human (Clark, 1977; Yabe et al., 2015).

It is clear that some remediation approaches are needed in this area. Although the number of scientific reports is few, we have identified that several remediation approaches have already taken. One of the approaches is to use plants (i.e. phytoremediation, Reilly & Reilly, 1973; Leteinturier et al. 2001). Plants are able to remediate heavy metals using different mechanisms, for example, they may be able to extract heavy metals and the plants can be taken away from the area to cleanse the contaminated soils. Contrastingly, plants can also be used to stabilize the heavy metals in soils, preventing them from escaping to other ecosystems (e.g. to groundwater or to other soil surfaces as dust). Either way, the societal implementation of the phytoremediation approaches can be efficient when locally available or indigenous species are used.

Thus, better understanding of the plant community structures is needed in Kabwe area. In fact, Leteinturier et al. (2001) conducted intensive surveys for plant communities at the Kabwe mining area and nearly 40 species were reported. However, these previous surveys were performed within the mining site, not targeting the whole Kabwe township where citizens are living. Also, the survey was performed at the end and the beginning of wet season (Apr and Nov), and the information during the driest time of the year (i.e. July–Sep) were missing. We believe that plants surviving in the dry season are critically important in terms of their potential use as phytoremediation methods. Plants that become dominant during the dry season might be difficult to efficiently stabilize the lead containing soils because we observed that extensive amount of fine soil particle (dust) has been blown off during the dry season and plants may reduce the amount of dust. Thus, perennial plants might have some advantages because they maintain their growth in the field when soil erosion risks are higher (Andreazza et al. 2011).

Additionally, the adaptation (survival) of plant species and their efficacy in terms of soil stabilization are often influenced by soil types. Thus, detailed soil mapping is very important. Spectral sensing approaches can be an option to differentiate soil types according to their spectral curves, and are done using satellite data (Nanni et al. 2012). Soil properties such as soil moisture contents can also be quantified using the spectral data (Weidong et al. 2002). Also, the availability (mobility) of Pb in soils is another factor has to be considered to plan efficient phytoremediation approaches. Generally, in soils, plant available Pb contents are very small when compared to the total Pb contents. Thus, better understanding of the amount of available Pb in soils is required not only to investigate the plant survival rates but also to investigate the risk of Pb leaching to water ecosystems (Gleyzes et al. 2002).

Thus, in this study, we have researched plant community structures and land spectral images at various places in Kabwe city. Also, some basic information on soil Pb characteristics were also studied.

2. Research methods

2.1. Research sites

The field survey was conducted from 5th July to 8th July 2016, in Kabwe city, Zambia. The sites where we sampled our soils and plants were stated in Fig. 1. From the mine residue damping zone (“022_DUMP” in Fig. 1, 14°27′44′′S, 28°25′51′′E), we covered 0–5 km zones towards all the directions. The detailed description of each site was also stated in Table 1 and as described, there were missing data for some sites due to reasons such as disturbances by local people. Due to scarce rainfall during this period, most of the sites were dry but we also found some wetlands particularly in northern part of the city (sites “015_dambo”, “016_dambo”, and “017_dambo_bridge”), where soils were saturated (Photo 1).

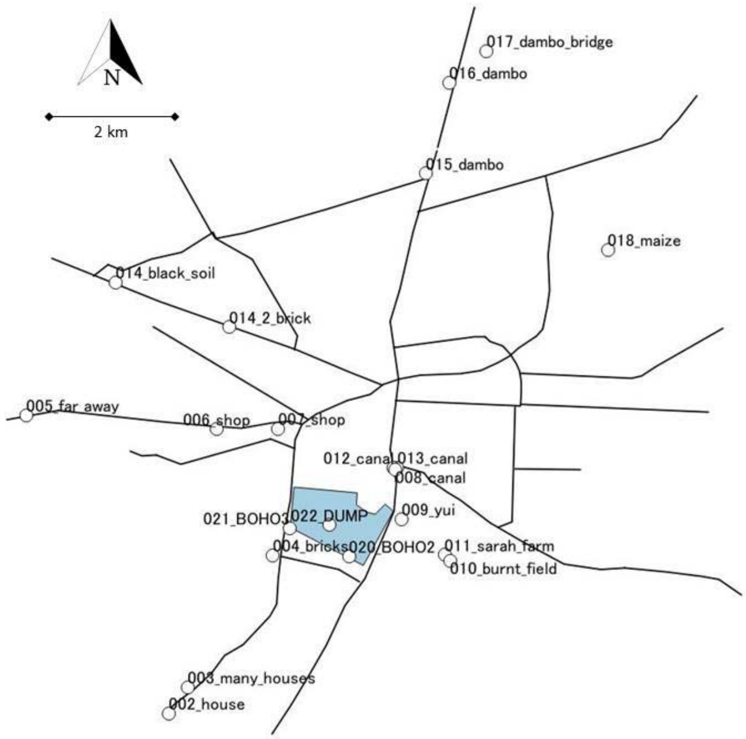

Figure 1. Major roads in Kabwe city, Zambia and our field survey sites (white circles). The shaded area was the mine residue dump site. The center of the sampling sites, “022_DUMP” was at 14°27′44′′S, 28°25′51′′E. The map is North on the top and the 2 km scale bar is shown on the map.

Table 1. Detailed description of the field survey sites.

Distance from the mine (m)	Soluble Pb data	Soil XRF data	Spectral image data	Plant community information	Site name	Number
3,787	Yes	Yes	Yes	No	002_house	1
3,298	Yes	Yes	Yes	No	003_many_houses	2
987	Yes	Yes	No	No	004_bricks	3
4,956	Yes	Yes	Yes	No	005_far_away	4
2,275	No	No	No	Yes	006_shop	5
1,674	No	No	No	No	007_shop	6
1,334	Yes	Yes	No	No	008_canal	7
1,112	Yes	Yes	No	No	009_yui	8
1,928	Yes	Yes	No	Yes	010_burnt_field	9
1,821	Yes	Yes	No	No	011_sarah_farm	10
1,323	No	No	No	No	012_canal	11
1,349	Yes	Yes	No	No	013_canal	12
4,954	Yes	Yes	Yes	Yes	014_black_soil	13
3,391	No	No	Yes	Yes	014_2_brick	14
5,556	Yes	No	No	No	015_dambo	15
6,903	No	No	No	Yes	016_dambo	16
7,626	No	No	No	Yes	017_dambo_bridge	17
5,993	Yes	Yes	Yes	Yes	018_maize	18
577	No	Yes	No	Yes	020_BOHO2	19
613	No	Yes	No	No	021_BOHO3	20
0	No	Yes	No	Yes	022_DUMP	21

Photo 1. (Left) Dry abandoned field (site "018_maize") and (Right) wetland site (site "016_dambo") (taken on July 6th, 2016).

2.2. Plant survey

At each plant survey sites (Fig. 1), we visually observed the plant species. To identify species, van Wyk and van Wyk (2013) and Pienaar and Smith (2011) were referred as well as communications with locals.

2.3. Measurement of soil lead concentrations using X-ray fluorescence approaches (XRF) and a portable colorimetric lead measurement kits

Approximately 200 g of soils were taken from each soil sampling site. They were placed in plastic bags and measured for total Pb concentrations using a portable XRF analyzer (Innov-X Alpha Series^{TM} Advantages, Innov-X Systems, Inc. USA). The portable XRF analyzer indicated only "total" amount of Pb and did not indicate the availability of the metal for plants. Thus, the soils were sampled from the field and were extracted with hot-water (80°C, 1 hour, soil:water = 1:10) to obtain "water soluble" proportion of the total Pb. The supernatant was analyzed for the soluble Pb concentrations using a colorimetric kit (PACKTEST Lead, model SPK-Pb, Kyoritsu Chemical-Check Lab., Corp. Japan). Also, some surface and groundwater were analyzed for soluble Pb, using the same kit.

2.4. Spectral sensing

We used a portable spectral sensor to investigate the spectra of land surfaces in different areas in Kabwe. The compact hyperspectral sensor with a USB camera (MCM-4304, Micro Vision Co., Ltd. Japan) was used. The measurement was taken using following approaches, as explained in Fig. 2. First, a total reflection at each soil measurement site was obtained by taking a spectrum of a white filter paper (Tokyo Roshi Kaisha, Ltd. Japan). Then, a soil spectrum was measured without moving the sensor (the sensor was secured on a stand, as shown in Fig. 2). We took five replicates for each sample. For the data analyses, ImageJ software (ver. 1.6.0_24, National Institutes of Health, USA) was used. First, the spectral data was converted to numbers depending on the strength of white. Then, the X axis was calibrated to express it as the wavelength using a Hg light value. Spectral data of Hg light has some specific peaks that are known as intrinsic wavelengths (Sansonetti et al. 1996). To convert the intensity of white into a reflectance, the data from the soil samples were divided by the spectral data taken from a white filter paper.

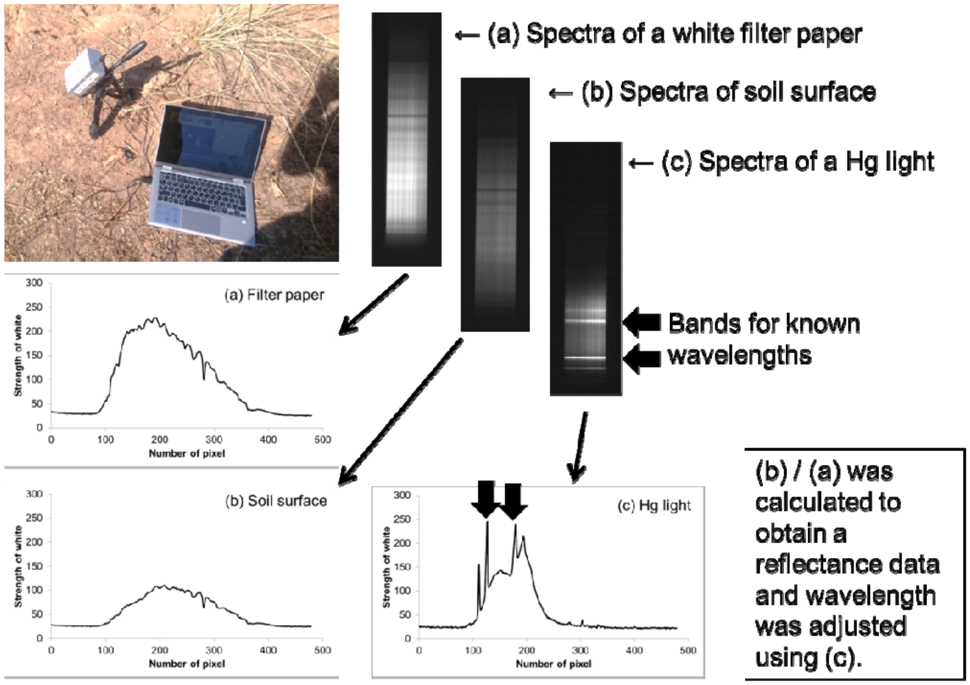

Figure 2. A diagram explains processes of the measurement of soil spectra. We took spectra of (a) a white paper, (b) soil and (c) a Hg light. These image data were converted into text files for further calculation, using the ImageJ software. The number of pixel from each data was calibrated to calculate the wavelength, based on the data obtained from a Hg light. The ratio of (b) to (a) was used to calculate a reflectance. The image data was obtained from a USB camera, embedded within the compact hyperspectral sensor system was used to obtain the data. The data collection was performed in the area without shaded area to maximize the strength of light.

3. Research activities and snapshots of the preliminary findings the field survey in Kabwe city

3.1. Observed plant species

The plant communities in Kabwe were recorded in details by Leteinturier et al. (2001). The most of plants we have found in Kabwe were found in this previous report and we have identified in total of 20 plant species (Table 2). The survey conducted in the current study was not intensive enough to discuss the effect of the mine residue on plant community structures or diversities. On the mine residue itself, a large number of African fountain grass species (*Pennisetum setaceum*) was observed. According to a verbal communication with the landowners, this species has been markedly increasing over the last decades and helped reducing the dust blowing around the residues. In a wetland site (site 016), totally different plant community structures were observed, including *Phragmites* and *Ipomoea*. This suggests that the availability of water is probably one of the major factors controlling the plant community structures in Kabwe area. Further studies are needed in terms of their characteristics in relation to the mobility of heavy metals.

Table 2. Plant species observed in Kabwe, Zambia, during a dry season (July 2015). Plant species were visually determined using Leteinturier et al. (2001), van Wyk and van Wyk (2013) and Pienaar and Smith (2011). The "+" sign means that we observed the species in each site. The site names were in the order of the distance from the mine (m), from left to right.

6,093	5,993	5,556	4,954	3,391	2,275	1,349	1,112	613	0	Distance from the mine (m)	
016	018	015	014	014_2	005	013	009	020	022	Family/Site name	Species
		+								Asteraceae	*Ageratum conyzoides* L.
	+									Amaranthaceae	*Amaranthus dubius* Mart. ex Thell.
							+			Papavaceae	*Argemone mexicana*
				+	+	+	+			Caesalpiniaceae	*Bauhinia petersiana bolle*
		+		+						Asteraceae	*Bidens oligoflora* (Klatt) Wild
			+							Asteraceae	*Bidens pilosa*
									+	Amaranthaceae	*Celosia trigyna*
										Fabaceae	*Crotalaria agatiflora*
									+	Poaceae	*Cynodon dactylon* (L.) Pers.
						+				Cyperaceae	*Cyperus involucratus* Rottb.
									+	Asteraceae	*Flaveria trinerva* (Spreng.) Mohr
+										Convolvulaceae	*Ipomoea cairica* (L.) Sweet
						+				Fabaceae	*Lebeckia cytisoides*
								+	+	Poaceae	*Pennisetum setaceum* (Forssk.) Chiov.
+								+		Poaceae	*Phragmites mauntianus* L.
			+							Euphorbiaceae	*Ricinus communis* var. *communis*
			+							Solanaceae	*Solanum incarnum* L.
			+							Boraginaceae	*Trichodesma zeylanicum* (Burm f.) R Br.
	+		+							Asteraceae	*Tridax procumbens* L.
			+			+				Asteraceae	*Vernonia erinacea* Wild

3.2. Heavy metal concentrations in surface soils

Based on our XRF measurements, the total Pb contents in soils ranged from 20 ppm (site 014_2_brick) to 10,000 ppm (site 008_canal). There was a weak but positive relationship between the total and water soluble Pb contents (Fig. 1a). The water soluble Pb contents ranged from 0 to 4 ppm and it was in general less than 1% of the total Pb. We believe that soil characteristics (e.g. parent materials and clay contents) are the major factors controlling the ratio between the total and water soluble Pb. Further research is needed in this area because water soluble Pb can be more mobile and hold higher risk of plant and animal absorption.

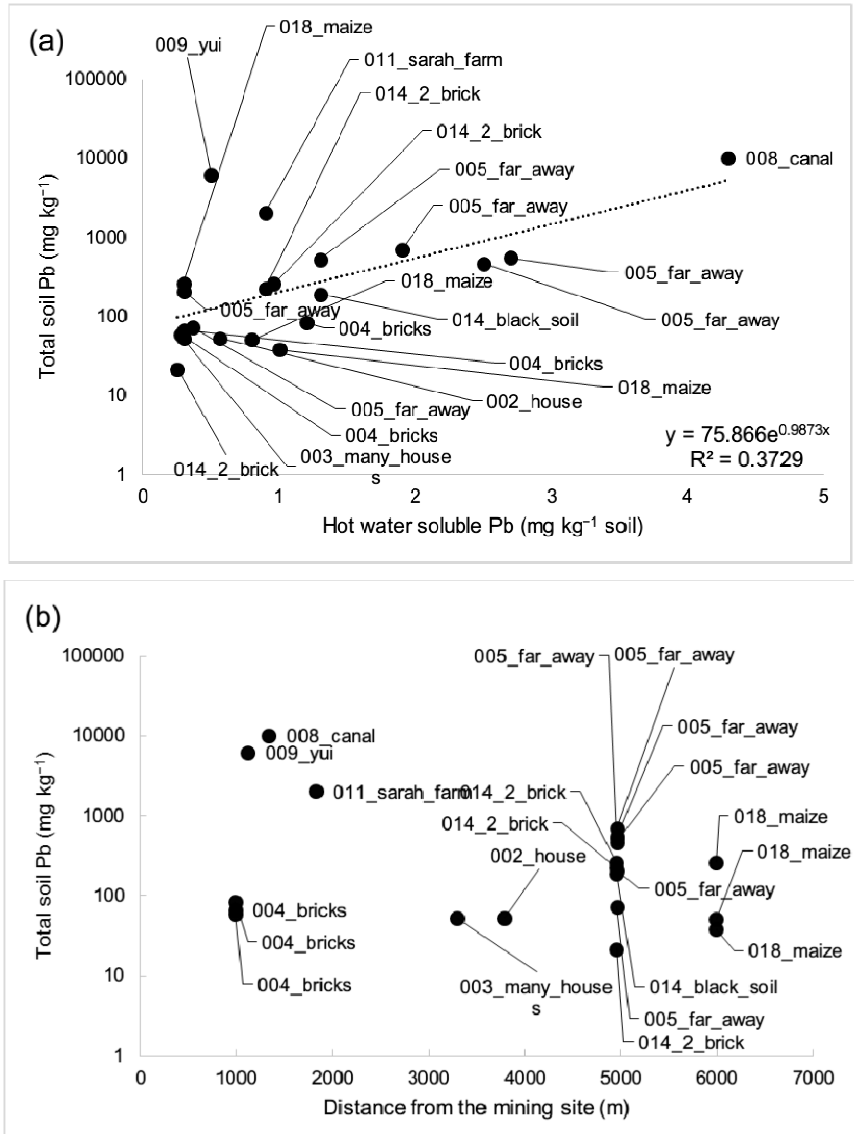

Figure 2. (a) The correlation between hot-water soluble lead concentration and total lead concentration and (b) the correlation between the total lead concentration and the distance from the mine site (site 022). The Y axes were shown as a log-scale. For the detailed description of the site, please see Fig. 1 and Table 1.

3.3. Spectral characteristics of the site

Figure 3 shows photos of some soil samples with their reflectance data. The soil obtained from the site 005 was brighter in color and its spectrum shows a difference compared to other soils, specifically in red wavelength region (~650 nm). Also, the spectrum from the soil 014 showed a characteristic shape. Based on personal communications, natives in Kabwe regard this soil as a relatively more fertile one (called "black soil"). The identification of this soil seems promising based on our preliminary data. In this discussion, we do not take the influence of soil moisture into consideration since the soils appeared to be dry. We would focus on the spectral effects of soil moisture in the future analyses.

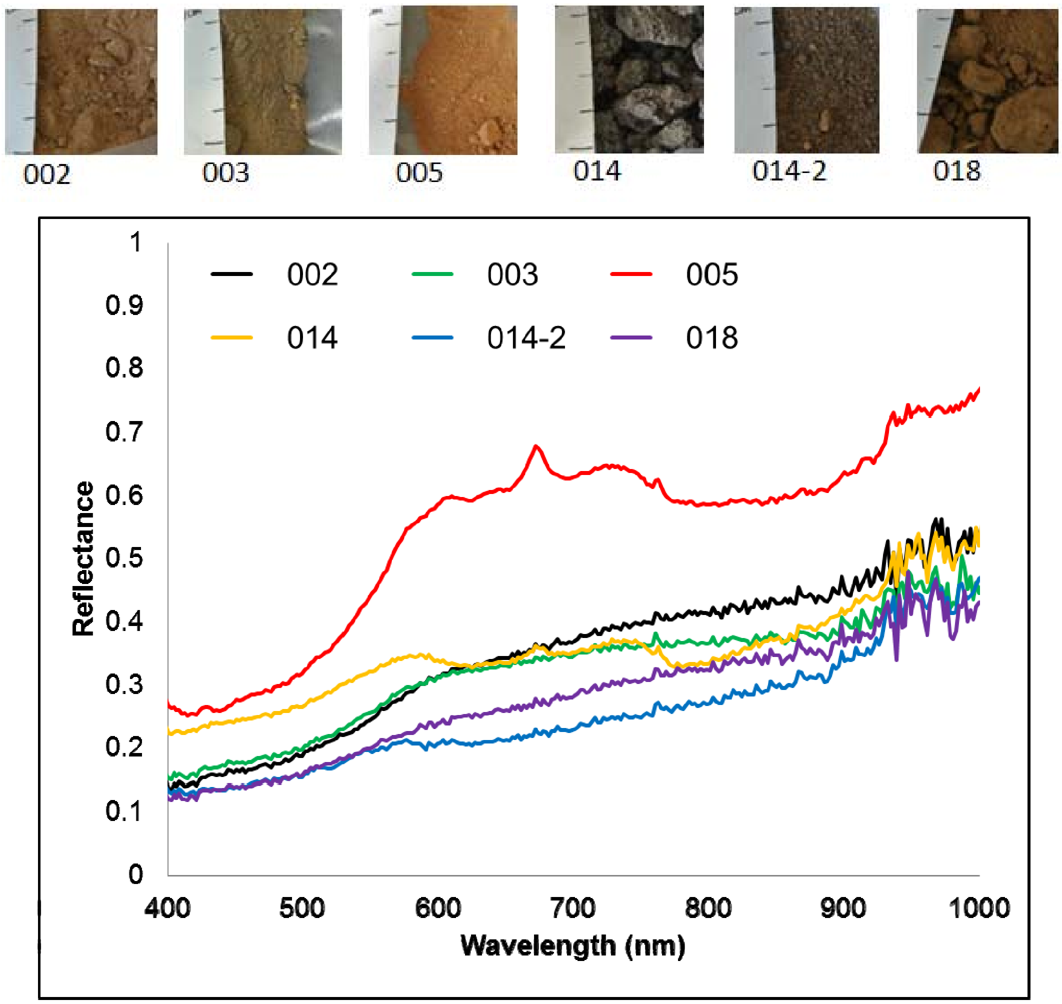

Figure 3. Photos of some of the sampled soils in Kabwe (above) and the reflectance of them (below).

4. Conclusion

This preliminary field survey clearly indicated that the extensive area within Kabwe is contaminated by Pb. Our plant community structure observation revealed that plant species such as *Caesalpiniaceae* and *Fabaceae* families remained active during the dry season, potentially be utilized to stabilize the contaminated soils. The percentage of water soluble Pb in relation to the total soil Pb was <1% but the extreme values were observed within 2 km zone from the mining site. The preliminary taken spectral curves suggested that remote-sensing techniques may be used to differentiate soil types. Further studies should focus on more detailed analyses of plant communities as well as their capacities to stabilize soils and Pb. Also, soil moisture has to be taken into account to further evaluate the potential use of spectral images in this area.

Acknowledgements

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