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Community-Based Research on Heavy Metal Soil Contamination in Urban West Atlanta

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Bachelor of Science
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Thesis Committee Chair: Eri Saikawa, Ph.D.

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Abstract

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INTRODUCTION: Heavy metal soil contamination is a major environmental issue. Elevated heavy metal soil concentrations significantly impact soil, plant and human health. This project was a community-engaged research project, in collaboration with Historic Westside Gardens (HWG), Environmental Protection Agency (EPA), and the Georgia Department of Public Health. The aims of this study were: (1) to assess baseline levels of heavy metal soil concentration levels in urban West Atlanta; and (2) to assess relationships among heavy metal soil concentrations and their bioavailability in the mimicked gastrointestinal environment.

METHODS: 15 urban agricultural and residential sites were sampled in partnership with HWG throughout West Atlanta, using snowball sampling. All soil samples were analyzed for heavy metal concentrations, using x-ray fluorescence (XRF). 38 soil samples ranging from 200 to 1000 ppm Pb concentration were chosen to process the bioavailability experiment using stomach and intestine physiological based extraction tests (PBET). Our team estimated the bioavailable concentrations of eight different heavy metals at each step and the total heavy metal soil concentrations through inductively coupled plasma (ICP).

RESULTS: Some sampling sites had heavy metal soil contamination in urban West Atlanta. Several selected heavy metal concentrations (e.g. arsenic (As) vs. lead (Pb) and Pb vs. zinc (Zn)) had high correlations. Additionally, only Pb and Zn heavy metal soil concentrations had strong correlations with their bioavailablity. The average total bioavailable concentrations of Pb and Zn exceeded the University of Georgia (UGA) risk reduction standard for agricultural soil. This study also found that there were strong correlations between soil concentration of Pb and Zn, analyzed using XRF and ICP. Compared to ICP measurements, XRF measurements tended to overestimate the heavy metal concentrations of As, barium (Ba), cadmium (Cd), chromium (Cr) and nickel (Ni).

CONCLUSION: For Pb, XRF measurements were highly correlated with ICP measurement and soil Pb heavy metal concentration had a strong correlation with Pb bioavailability. This research provided confidence that XRF was a reliable for detecting soil Pb concentrations. This study also highlighted the importance of reporting the total bioavailable concentrations and percentage to make meaningful conclusions about health impacts.

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1. Introduction

1.1. Impacts of Heavy Metal

Heavy metal soil contamination negatively impacts soil enzymes and microbes, plants and human health. Heavy metals often accumulate in soil through human activities, such as the use of lead (Pb) paint and coal combustion (Khan et al., 2009; Wuana and Okieimen, 2011). Elevated heavy metal concentrations in soil affects the soil enzymatic activities, leading to adverse effects such as a decrease in microbial diversity (Chen et al., 2014). Soil enzymatic activities and microbial diversity both play significant roles in the recycling of plant nutrients, maintenance of soil structure and detoxification (Jiwan, 2011). Additionally, different soil enzymes display different sensitivities to heavy metals (Jiwan, 2011). For example, copper (Cu) inhibits b-glucosidase activity significantly. Cadmium (Cd) has greater mobility and lower affinity than other metals in soil colloids (Jiwan, 2011). Therefore, accumulated heavy metals by historical human activities can directly impact soil by affecting soil enzymatic activities and microbial diversity, leading to irreversible consequences such as inefficient maintenance and detoxification of soil.

Heavy metals (e.g. arsenic (As), Cd, Cu, Pb) are mobile and toxic to plants, and they can enter plants by transferring from soil solution into roots (Intawongse and Dean, 2006; Chojnacka et al., 2005). For instance, As and Cd lead to a decrease in seed germination, seedling height and protein content of maize and wheat (Marin et al., 1993; Abedin et al., 2002). Cu reduces biomass, seed production, enzymatic activity, leading to plant mortality (Sheldon and Menzies, 2005). High levels of Pb contamination could cause death of some plants such as Lythrum salicaria in a short-time period (Nicholls and Mal, 2003). Based on extensive research, heavy metals have the ability to transfer into soil solution and significantly affect plant growth by inhibiting physiological metabolism and damaging cell structures (Intawongse and Dean, 2006).

Ingestion is the major pathway through which humans are exposed to heavy metals from soil (Jiwan, 2011). Based on the research of the Environmental Protection Agency in the United States (US EPA), the daily amount of soil ingestion per person is estimated to be 50 to 200 mg/day. For children aged 1 to 6 years without the soil-pica behavior, the estimation is about 100 mg/day. For children up to age 14 with soil-pica behavior, the estimation is about 400 to 41,000 mg/day. Hence, heavy metal soil contamination poses a particular hazard to children because of hand-to-mouth behavior (Karadaş and Kara, 2011).

Chronic level ingestion of toxic metals (e.g. Cd, Pb, As) has harmful impacts on humans. The kidney is usually the first target organ of heavy metal pollutants toxicity, because approximately 50% of the reabsorbed and accumulated dose is stored in there (Henry et al., 2015; Johri et al., 2010; Barbier et al., 2005). Specifically, long-term exposure to low levels of Cd has been associated with bone mineralization, glomerular damage, end-stage renal failure and deranged blood pressure regulation (Martin and Griswold, 2009; Satarug and Moore, 2004; Johri et al., 2010). Moreover, chronic ingestion of Pb can severely damage the hippocampus, cerebellum, and nervous system leading to behavioral disorders, dementia and anemia (Saleh et al., 2018; Finkelstein, 1998). Pb exposure also particularly impacts children, often resulting in learning difficulties and behavioral disturbances (Järup, 2003). Research shows that IQ declines by at least two points with an increase of 30 μg/dl in blood Pb level (Finkelstein, 1998). Additionally, long-term ingestion of low-level As can influence central nervous, gastrointestinal and cardiovascular systems (Järup, 2003). Therefore, long-term exposure to heavy metals through ingestion adversely influences human health to cause end-stage organ failure, behavioral disorders, cardiovascular diseases, and other health issues.

In summary, heavy metal soil contamination is a major environmental issue. Elevated heavy metal soil concentrations significantly impact soil and plant by affecting soil enzymatic activities and microbial diversity and inhibiting physiological metabolism and damaging cell structures. Heavy metal soil contamination also poses a particular hazard to human health by leading to end-stage organ failure, behavioral disorders, cardiovascular diseases, and other health issues. In order to reduce heavy metal soil contamination levels in the society, public health researchers and local communities need to spread awareness of the impact heavy metal contamination has on soil, plant and human health.

1.2. Bioavailability

The presence of heavy metals in soil itself does not necessarily imply that they are bioavailable to plants or the circulative system in humans, particularly if they are insoluble in the soil solution (Chojnacka et al., 2005). The bioavailability of a heavy metal indicates how much of the specific heavy metal can be dissolved in the gastrointestinal tract, absorbed through the intestine with large surface area and reach the systemic circulation (Intawongse and Dean, 2006; Ellickson et al., 2001). Oral bioavailability can be measured through *in vitro* gastrointestinal simulations where conditions including temperature, pH, enzyme, and chemical compounds are simulated to mimic those that can be found in the digestive system of human body (Karadaş et al., 2011). The oral bioavailability of heavy metals also depends on different physical and chemical factors in the soil. For instance, heavy metals become more soluble and mobile if the soil is acidic (Martin and Griswold, 2009). Moreover, some studies found heavy metal bioavailability to be related to the calcium(II) (Ca^{2+}) concentration of the soil (Walker et al., 2003). Hence, it is critical to determine the bioavailability to understand the possibility of dissolution and mobility of heavy metals in human bodies.

1.3. Potential Sources of Heavy Metals in Contaminated Soils

1.3.1 Lead-based paint

In the United States, Pb has been used for hundreds of years to produce Pb acid batteries, pesticides, pipes, pigments, building materials etc. (Greene, 1993; Järup, 2003). One of the previous uses of Pb is Pb-based paint, which is used as a protective coating on buildings throughout the country (Mielkel and Reagan, 1998). The Department of Housing and Urban Develop estimated that approximately 24 million personal housing currently contains Pb paint in unsound condition (U.S. Department of Housing and Urban Development, 2006). Extensive research showed that Pb-based paint contributes to soil Pb contamination through both airborne and mechanical transport into soil, especially for homes built before the 1970s (Mielkel and Reagan, 1998; Gulson et al., 1995; Binns et al., 2007).

Pb-based paint and soil Pb contamination are the most prevalent sources of Pb and are closely linked to Pb poisoning in children in the United States, especially in Georgia (Mielkel and Reagan, 1998). Pb poisoning is defined as a child with a Pb screened level higher than 5 μg/dL (Parker, 2018). Throughout Georgia, about 47% of personal homes are built pre-1970s, and Georgia Healthy Homes and Lead Poisoning Prevention (GHHLPPP) identified 206 homes with confirmed Pb hazards that have been directly linked to Pb-poisoned children between 2010 and 2012 (Fitzgerald and Deal, 2013). Based on the Georgia Lead Poisoning Prevention Program (GCLPPP) database and the annual report of Georgia Department of Public Health, there were 124,007 children less than 6 years old tested for Pb poisoning in 2017. Of these children, 2,462 were found to have a blood Pb level of 5-9 μg/dL, and 548 were found to have a blood Pb level of 10 μg/dL or greater. Meanwhile, 222 children aged less than 6 years old had 5 μg/dL or greater blood lead levels in DeKalb county, and an additional 159 and 173 children tested high in Fulton and Gwinnett county respectively. Based on the data provided, GHHLPPP identified these three counties throughout the state as the highest risk for lead poisoning in children (Fitzgerald and Deal, 2013).

Soil Pb contamination caused by Pb-based paint is the most prevalent cause of Pb poisoning in children. Children are the most vulnerable to Pb poisoning because of the hand-to-mouth behavior, and no safe blood Pb level has been identified for children (Silbergeld, 1997). Because the participating communities have a high percentage of older housing, Pb-based paint is a potential source of Pb in this study.

1.3.2. The Proctor Creek Watershed

The Proctor Creek watershed is located west of downtown Atlanta, Georgia, inside Atlanta's city limits (Samuel, 2017). This watershed flows through northwest Atlanta and into the Chattahoochee River (U.S. Environmental Protection Agency, 2018). The watershed includes 10,600 acres, 38 neighborhoods, 300 urban streams, and 127,418 residents (Haddock, 2017; Rehagen, 2013; Edwards, n.d.). Some neighborhoods along the watershed are economically depressed areas with high rates of poverty and crime (U.S. Environmental Protection Agency, 2018).

Due to decades of neglect and serious environmental challenges, such as stormwater flooding, soil erosion, combined with sewer overflows and illicit tire dumping, people living along the Proctor Creek watershed experience various public health issues and this watershed could influence the health of soil through infiltration (Edwards, n.d.). Based on 2015 and 2016 EPA reports of the Proctor Creek Watershed Monitoring Activity, significant amounts of the majority of targeted metals such as Pb, Cu, zinc (Zn), As, Cd, Ca and potassium (K) were found in surface water samples and sediment samples (U.S. Environmental Protection Agency, 2015; U.S. Environmental Protection Agency, 2016). In the 2015 EPA report, sediment samples from a number of the gauging stations had Cu and Pb concentrations (maximum Cu concentration: 43 mg/kg, and maximum Pb concentration: 100 mg/kg) that were above the threshold effect concentration (U.S. Environmental Protection Agency, 2015). This finding implies that sediment in the

Proctor Creek watershed may be toxic to aquatic organisms and humans, once ingested. In the EPA report of 2016, researchers found that one surface water sample collected from a tributary gauging station contained a Pb concentration level (9.1 μg/L) above the chronic exposure level, which could cause adverse health effects to humans, once ingested (U.S. Environmental Protection Agency, 2016).

1.3.3. Slag

Slag is produced during pyrometallurgical processing of various ores (Gorai et al., 2003). Different types of slag have different ranges of bulk chemistry, chemical composition and leachate chemistry (Piatak et al., 2015). For instance, ferrous slag generally contains significant concentrations of trace element including Ca, As, Cr, manganese (Mn), and iron (Fe), and non-ferrous slag is dominated by Fe, As, Cd, Cu, nickel (Ni), Pb and Zn (Piatak et al., 2015). Moreover, some metal-specific slag also exists, such as Zn slag, Pb-Zn slag, Ni slag, Cu slag, etc. Although slag does contain some potentially toxic elements, they still are used as construction materials and in environmental applications (Piatak et al., 2015). For example, ferrous slag has the ability to remove phosphorous and nitrogen from unwanted industrial emission, wastewater and agricultural runoff. Ferrous slag also can treat acid-mine drainage as an acid-neutralizing agent (Sun et al., 2009; Gahan et al., 2009).

The contamination of soils from slag cannot be ignored because of the potential health impacts from heavy metal ingestion through soil (Kasemodel et al., 2016). Recent studies found that through sequential extraction with acid hydroxylamine and substantial redistribution processes between slag and soil, metal ions can be released from slag and partially re-adsorbed by soil constituents (Bunzl et al., 1999). This process caused the contaminated soil to have elevated concentration of toxic trace elements including Pb, Cd, and Zn in the slag disposal areas (Kasemodel et al., 2016). Therefore, slag is a potential source of heavy metal contamination in soils.

1.4. Goals of Present Study

This study was a community-engaged research project, in collaboration with Historic Westside Gardens (HWG), EPA, and the Georgia Department of Public Health. The main goals were to work with the community in West Atlanta to assess baseline heavy metal contamination levels in the neighborhood and bioavailability to understand possible health impacts in urban West Atlanta. Our study enhanced the awareness of heavy metal contamination in urban soils among West Atlanta community members.

The aims of this study were: (1) to assess the baseline levels of heavy metal soil concentration levels in urban West Atlanta; and (2) to assess relationships among heavy metal soil concentrations and their bioavailability in the mimicked gastrointestinal environment. The hypothesis for the first aim was that there was no relationship between several selected heavy metal concentrations (e.g. As vs. Pb and Pb vs. Zn). The hypothesis for the second aim was that there was no relationship between heavy metal soil concentrations and their bioavailability in the mimicked gastrointestinal environment.

2. Materials and Methods

2.1. Site Selection

This project was conducted in collaboration with HWG, which is a conglomeration of urban gardens in homes and properties in West Atlanta. This project worked with the disadvantaged community in West Atlanta with high rates of poverty and food deserts. Snowball sampling method was used in this community-based study, because it provides connections with a hard-to-reach population. This study only used 15 sampling sites in total, which were all located in West Atlanta. Within these sites, ten of the sites were personal residential gardens and five sites were community gardens.

2.2. Soil Sampling and Analysis

In order to enumerate the baseline levels of heavy metal soil concentrations in urban Atlanta, this study used 281 soil samples collected from 15 sampling sites in total.

Incremental Sampling Methodology (ISM) was followed for each site. ISM is a structured composite sampling method that can reduce data variability and provide an unbiased estimate of pollutant concentrations in targeted soil sampling areas (ITRC, 2012). In order to visualize exposure routes and transport mechanisms, a conceptual site model was built for each sample site before sampling. Each site was divided into different decision units (DUs). Each DU represented soil with potentially different concentrations of heavy metals due to different plants or site history. After dividing each DU into 30 small grids, soil samples were collected from each of the grids in triplicate from the same depth of 2 inches. All soil samples were taken by a stainless-steel trowel and placed into a properly-labeled aluminum pan. Samples were then air-dried in a ventilation hood in the laboratory, broken up into small pieces and mixed evenly. In order to create a homogenous ISM sample, each soil sample was divided into 30 sections, sub-sampled, sieved to 150μm and 5 grams of fine soil were placed into a clear plastic bag. Processed final ISM samples were analyzed to quantify heavy metal concentrations, using x-ray fluorescence (XRF) provided by EPA. The XRF analyzed an area of 10 mm^2, penetrated to a 2mm depth of soil sample and detected concentrations of 32 different types of heavy metals at the same time (Moller et al., 2018). Three different wavelengths were emitted for 30 seconds each for a total of 90 seconds per sample. Each sample was measured four times to obtain representative 95% confidence limit at low cost. Quality control was achieved through the quality calibration check, which was conducted at the beginning of each working day and after the batteries were changed.

2.3. Bioavailability Assessment

The bioavailability of heavy metal contaminants for normal children and those with pica were estimated using the ingestion of contaminated soil as the main route of exposure. 38 soil samples ranging from 200 to 1000 ppm Pb concentration were chosen to process the bioavailability experiment using stomach and intestine physiological based extraction tests (PBET). First, metal grade hydrochloric acid and pepsin were used to simulate the environment of human stomach. The stomach solution was kept at a pH of 2.5 and a temperature of 37 degrees centigrade. The solution was stirred to mimic gastric mixing for one hour. After a one-hour reaction, 5 mL of stomach digestion solution was pipetted into a sterile test tube. Second, bile extract, pancreatin and sodium bicarbonate were used to create a human intestinal environment. The intestinal solution was kept at a pH of 7 and temperature of 37 degrees centigrade. After a one-hour reaction, another 5 mL of intestinal digestion solution was pipetted into a sterile test tube. Both digestion solutions were centrifuged at 4000 rpm for 20 minutes and the supernatant was removed. The bioavailable concentrations of eight different heavy metals from each digestion and the total heavy metal soil concentrations were measured using inductively coupled plasma (ICP).

2.4. Statistical Analysis

Statistical analyses were performed using ArcGIS version 10.6, SAS version 9.4 and R version 1.1.4. Descriptive analysis and correlation analysis were conducted to analyze the longitudinal data. For all analyses, a p-value of 0.05 was used to determine significance. A 95% confidence interval for heavy metal concentrations in each DU was calculated.

In this study, 14 metals (As, barium (Ba), Ca, Cd, Cd, Cu, Fe, K, Mn, Ni, Pb, S, titanium (Ti) and Zn) were analyzed among the 32 metals detected from XRF, due to limit of detection by XRF and minimal health impacts. Median, mean, standard deviation, minimum, maximum, range, and skewness of heavy metal soil contaminations were calculated. Additionally, these concentrations were compared with EPA regional screening levels (RSL) for residential soil and the University of Georgia (UGA) risk reduction standard for agricultural soil. In order to visualize spatial patterns and distribution of selected heavy metal soil contaminations of Pb, Cd and As, spatial maps were produced by using ArcGIS. Correlation matrices were produced to examine the correlations among the selected 14 heavy metals (e.g. As vs. Pb; Pb vs. Zn; and Ca vs. S). Pearson correlation coefficients of soil metal concentrations of eight bioavailable heavy metals (As, Ba, Cd, Cr, Mn, Ni, Pb and Zn), analyzed via ICP were calculated. Furthermore, stomach and intestinal heavy metal bioavailability was calculated as a percentage of heavy metal soil concentrations. The relationships between concentrations analyzed by XRF and ICP were visualized in histogram and scatter plots.

3. Result

14 different heavy metal concentrations are presented in Table 1 for all soil samples. The mean values of all heavy metal concentrations were below the EPA RSL for residential soil except Cr. The EPA RSL for Cr was specifically for Cr (VI), however, the measurements conduced by XRF were for total Cr. The mean values of Pb, As, Cd, Ba, and Zn were above the UGA risk reduction standard for agricultural soil. The maximum values of Pb, As, and Cr were above the EPA and UGA standards. The maximum values of Cd, Ba, Cu and Ni were above the UGA standard but below the EPA standard. The majority of heavy metal concentrations had a very high standard deviation (SD), illustrating the heterogeneity in the concentration levels across samples.

Spatial patterns and distribution of average and maximum heavy metal concentrations of Pb, Cd and As by sites are shown in Figure 1. Each figure contains three different spatial maps. The first spatial map shows west Atlanta, including all 15 sites. The second spatial map shows all of urban Atlanta. The last spatial map presents a closer look at the four overlapping sites, with each circle presenting one site.

Figure 1a shows the average soil Pb concentration by site. Only four sites contained average Pb concentrations that were below the UGA standard (75 ppm): Agr2 (62 ppm), Agr3 (64 ppm), Agr4 (59 ppm), and Res7 (39 ppm). Three sites contained average Pb concentrations above EPA standard (400 ppm): Res2 (684 ppm), Res9 (628 ppm) and Res10 (582 ppm). Approximately half of the sites had average Pb concentrations between 75 and 250 ppm (53%). As for the maximum Pb soil concentrations among the sites, only Res7 (66 ppm) was below the UGA standard (Figure A1a). Six sites contained maximum Pb concentrations above EPA standard, including Res2 (1263 ppm), Res3 (577 ppm), Res4 (577 ppm), Res9 (1019 ppm), Res10 (596 ppm) and Agr2 (456 ppm).

Figure 1b shows the average soil Cd concentrations at each site. Res6 (28 ppm) had the highest average Cd soil concentration and the Cd concentrations at all sites were above the UGA standard (2 ppm). As for the maximum Cd soil concentrations among the sites, Agr4 (55 ppm) and Res9 (47 ppm) had higher maximum Cd concentrations than others but were still below the EPA standard (210 ppm) (Figure A1b). Approximately half of the sites contained maximum Cd soil concentration between 10 to 20 ppm (53%).

The average soil As concentrations were above the UGA standard (20 ppm) in three out of 15 sites (Figure 1c): Res2 (28 ppm), Res9 (36 ppm) and Res10 (25 ppm). Out of the 15 sites, nine sites contained average As concentrations between 0 to 10 ppm. Six sites contained maximum As soil concentration above the UGA standard (Figure A1c): Res2 (54 ppm), Res3 (32 ppm), Res4 (32 ppm), Res 9 (41 ppm), Res10 (26 ppm) and Agr1 (57 ppm).

Correlation matrices among 14 metal concentrations are shown in Figure 2. In the figure, the distribution of each heavy metal is shown on the diagonal. The distributions of Cr, Fe, K, Mn and Ti were nearly normal. The distributions of As, Ba, Ca, Cd, Cu, Ni, Pb, S and Zn were right-skewed. The scatter plots were used to investigate the correlations between two paired heavy metals displayed on the bottom of the diagonal. Scatter plots of As, Cu, S, and Zn had few outliers. Pearson correlation coefficients are shown on the top of the diagonal. A few paired heavy metals had strong correlations. As was correlated with Cu, Ni, Pb and Zn (r=0.72, 0.64, 0.76, and 0.76, respectively). Pb was highly correlated with Zn (r=0.92). Cr was correlated with Ti (r=0.66). Ca was correlated with S (r=0.68) and Cu, K, and Ti were all correlated with Ni (r=0.52, 0.61, and 0.52).

Table 2 shows the Pearson correlation coefficients of heavy metal soil concentrations and eight heavy metals bioavailability (As, Ba, Cd, Cr, Mn, Ni, Pb and Zn) in the mimicked gastrointestinal environment. Only soil Pb and Zn heavy metal concentrations had strong correlations between their intestinal, stomach and total bioavailable concentrations. For instance, soil Pb concentration was correlated with intestinal Pb, stomach Pb and total available Pb levels (r=0.77, 0.66, and 0.70 respectively). Some other heavy metal soil concentrations, such as As, Cd and Cr, only correlated with their intestinal or stomach bioavailable concentrations. Soil As concentration was only correlated with intestinal As and total available As (r=0.69 and 0.56 respectively). Additionally, soil Ba, Mn and Ni concentrations had no strong correlations with their bioavailablity at all.

The percentage of stomach and intestinal heavy metal bioavailability of soil concentrations for detected eight metals are shown in Figure 3. 38 soil samples were separated into three different groups depending on soil Pb concentrations, analyzed using XRF. The first group was soil Pb concentrations ranging from 200 ppm to 500 ppm; the second group was soil Pb concentrations ranging from 500 ppm to 700 ppm; and the third group was soil Pb concentrations ranging from 700 ppm to 1000 ppm. The percentage of bioavailable Ba concentration of the second group was the highest and was 92% meaning that 92% of soil Ba concentrations would exit the human body. Cd also had high bioavailability. The percentage of bioavailable Cd concentration of the third group was the second highest and was about 82%. Cr was the least bioavailable metal. Additionally, for the majority of heavy metals, stomach heavy metal concentrations were larger than intestinal heavy metal concentrations, except for As. More importantly, about 13 % of Pb of the third group was absorbed into the bloodstream and the average total bioavailable concentration of Pb (104 ppm) exceeded the UGA risk reduction standard for agricultural soil (75 ppm). The average total bioavailable concentrations of Zn for all three groups (142 ppm, 145 ppm and 260 ppm respectively) also exceeded the UGA risk reduction standard for agricultural soil (100 ppm).

In summary, the results in Figure 3 illustrated that the bioavailable heavy metal concentrations reaching the human systemic circulation were relatively lower than soil heavy metal concentrations. The results also highlighted the importance of considering not only the percentage of bioavailable heavy metal concentrations, but also absolute values when considering the health effects of heavy metals after soil ingestion.

Figure 4 shows the differences between the heavy metal soil concentrations of eight different heavy metals (As, Ba, Cd, Cr, Mn, Ni, Pb and Zn), using XRF and ICP. There were strong correlations between soil concentrations of Pb and Zn, analyzed using XRF and ICP (r=0.87 and 0.58 respectively). Additionally, comparing to ICP measurements, XRF measurements tended to overestimate the heavy metal concentrations of As, Ba, Cd, Cr and Ni.

4. Discussion

Depending on which standard was used in the analysis, this study found that there was a large difference in the perceived risk of different heavy metals in the soil samples. The UGA threshold for agricultural soil is much lower than the EPA RSL. For instance, 119 out of 281 soil samples exceeded the UGA standard for Pb. On the other hand, there were only 33 out of 281 soil samples that exceeded the EPA RSL for Pb.

There are various reasons why urban soils in West Atlanta are contaminated with heavy metals. It is possible that the sampling sites with old homes contained elevated Pb concentrations because the old homes with Pb-based paint were not demolished properly. Additionally, some sampling sites were close to the Proctor Creek, which may have contaminated the soil as well. Close to residential sites 3 and 4, a slag dump site was discovered. The slag samples contained extremely high levels of As, Pb and Fe. For the sampling sites with slag, the soil samples had elevated concentrations of As and Pb as well. This discovery prompted government organization such as EPA to cleanup and investigate into other potential slag sites in urban West Atlanta.

A null hypothesis that there was no relationship between several selected heavy metal concentration levels was rejected. These correlations could potentially help us determine the sources of heavy metal soil contamination. However, the soil contamination sources often varied at each different sample sites, and it was difficult to make a final conclusion, with limited information. Our results can provide some clues for a future study to determine the source of contamination.

This study only partially negated the second hypothesis that there was no relationship between heavy metal soil concentrations and their bioavailability in the mimicked gastrointestinal environment. Pb and Zn heavy metal soil concentrations had strong correlations with their bioavailability. The other heavy metals were only correlated with their intestinal or stomach bioavailable concentrations, or had no strong correlations at all. This finding illustrated that soil concentrations may only be a good indicator for the bioavailability of Pb and Zn. Other heavy metals may need another indicator to assess the health effects. For all detected heavy metals, the bioavailable heavy metal percentage of heavy metal soil concentrations was relatively low and for six out of eight metals (As, Cr, Mn, Ni, Pb and Zn), as the bioavailable percentages were smaller than 50%. It means that over 50% of heavy metal concentrations would exit the human body, even after being accidentally take in. The average total bioavailable concentrations of Pb and Zn exceeded the UGA risk reduction standard for agricultural soil. Such results indicate the importance of having a bioavailablity standard for heavy metals. This study also showcased the importance of reporting both the total bioavailable concentrations and the bioavailable percentage to make meaningful conclusions about health impacts.

This research also showed that community engagement at each step of the study improved the scientific and policy implications. Collaborators at EPA and Georgia Department of Public Health were essential in trying to solve the slag disposal problem right after the slag discovery. All the results were shared with community members and the feedback from them had a great impact on the research design and execution of the project. Furthermore, some sampling sites also had children who interacted with soil with their bare hands. Therefore, education and awareness of heavy metal exposure and the consequences of it was important for the community, especially for parents and children.

This study had a few limitations. First, the XRF measurement could not detect Cr(VI). The data exported from the XRF was for total Cr. Cr(VI) is extremely toxic to humans with an EPA RSL of 30 ppm. Compared to Cr(VI), EPA RSL for Cr(III) is 350,000 ppm. Second, all the soil samples for this study were collected from the same depth. According to previous research findings, heavy metal concentrations may vary with depth in urban soil, which can imply the potential sources of contamination (Luo et al., 2015). For sampling sites with slag, the source of heavy metal contamination is most certainly slag. For other sampling sites, it is potentially important for us to determine potential sources by collecting different vertical soil samples. For example, if the heavy metal concentrations decrease as deeper in the soil, then that might imply that the source of contamination is from the surface of soil, such as Pb-based paint or Proctor Creek (Nemati et al., 2011). Third, Our team could not separate pure compost samples and native soil samples when I conducted soil sampling. Compost application is one of the most-effective methods to maintain and improve soil structure (Ayari et al., 2010; Chen et al., 2015). However, poor-quality composts can often have high levels of heavy metal and toxic organics. It may be useful to create a survey about basic gardening information including compost, year of house etc. in a future study.

5. Conclusions

Through the study, I provided the baseline levels of 14 different heavy metal soil concentrations and bioavailability of detected eight different heavy metals in urban West Atlanta, which could benefit remediation research in the future. I found that some sampling sites had heavy metal soil contamination in urban West Atlanta. Several selected heavy metal concentrations (e.g. As vs. Pb and Pb vs. Zn) had high correlations. Additionally, only Pb and Zn soil heavy metal concentrations had strong correlations with their bioavailablity. The average total bioavailable concentrations of Pb and Zn exceeded the UGA risk reduction standard for agricultural soil. This study highlighted that for Pb, XRF is a reliable measurement to analyze soil concentrations and assess health effects. For Pb, XRF measurement was highly correlated with ICP measurement and Pb soil heavy metal concentration had strong correlation with its bioavailability. This study also showcased the importance of reporting both the total bioavailable concentrations and the bioavailable percentage to make meaningful conclusions about health impacts. My results support the need for establishing heavy metal bioavailability standards for children and adults.

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7. Reference

Abedin, M. J., Cotter-Howells, J., and Meharg, A. A. (2002). Arsenic uptake and accumulation in rice (Oryza sativa L.) irrigated with contaminated water. *Plant and Soil*, 240(2), 311–319.

Ayari, F., Hamdi, H., Jedidi, N., Gharbi, N., & Kossai, R. (2010). Heavy metal distribution in soil and plant in municipal solid waste compost amended plots. *International Journal of Environmental Science & Technology*, *7*(3), 465–472.

Barbier, O., Jacquillet, G., Tauc, M., Cougnon, M., & Poujeol, P. (2005). Effect of Heavy Metals on, and Handling by, the Kidney. *Nephron Physiology*, *99*(4), p105–p110.

Binns, H. J., Campbell, C., & Brown, M. J. (2007). Interpreting and Managing Blood Lead Levels of Less Than 10 g/dL in Children and Reducing Childhood Exposure to Lead: Recommendations of the Centers for Disease Control and Prevention Advisory Committee on Childhood Lead Poisoning Prevention. *Pediatrics*, 120(5), e1285–e1298.

Bunzl, K., Trautmannsheimer, M., & Schramel, P. (1999). Heavy Metals in the Environment: Partitioning of Heavy Metals in a Soil Contaminated by Slag: A Redistribution Study. *Journal of Environmental Quality*, 28(4), 1168- 1172.

Chen, J., He, F., Zhang, X., Sun, X., Zheng, J., & Zheng, J. (2014). Heavy metal pollution decreases microbial abundance, diversity and activity within particle-size fractions of a paddy soil. *FEMS Microbiology Ecology*, 87(1), 164–181.

Chen, M., Xu, P., Zeng, G., Yang, C., Huang, D., & Zhang, J. (2015). Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: Applications, microbes and future research needs. *Biotechnology Advances*, *33*(6), 745–755.

Chojnacka, K., Chojnacki, A., Górecka, H., & Górecki, H. (2005). Bioavailability of heavy metals from polluted soils to plants. *Science of The Total Environment*, 337(1–3), 175–182.

Edwards, C. (n.d.). Making a visible difference: Atlanta's Proctor Creek. *U.S.*

Environmental Protection Agency. http://www.EPA.GOV/REGION4

Ellickson, M., Meeker, R. J., Gallo, M. A., Buckley, B. T., & Lioy, P.J. (2001). Oral Bioavailability of Lead and Arsenic from a NISTStandard Reference Soil Material. *Archives of Environmental Contamination and Toxicology*, *40*(1), 128–135.

Finkelstein, Y. (1998). Low-level lead-induced neurotoxicity in children: an update on central nervous system effects. *Brain Research Reviews*, *27*(2), 168–176.

Fitzgerald, B., & Deal, N. (2013). Georgia Healthy Homes: Healthy Homes and Lead Poisoning Prevention Prgram. *Georgia Department of Public Health*.

Gahan, C.S., Cunha, M.L., & Sandström, Å. (2009). Comparative study on different steel slags as neutralising agent in bioleaching. *Hydrometallurgy*, 95, 190–197.

Järup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin*, *68*(1), 167–182.

Gorai, B., Jana, R. K., & Premchand. (2003). Characteristics and utilisation of copper slag—a review. *Resources, Conservation and Recycling*, *39*(4), 299–313.

Greene, D. (1993). Effects of lead on the environment. *LEAD Action News*, 1(2). http://www.lead.org.au/lanv1n2/lanv1n2-8.html

Gulson, B. L., Davis, J. J., & Bawden-Smith, J. (1995). Paint as a source of recontamination of houses in urban environments and its role in maintaining elevated blood leads in children. *Science of The Total Environment*, 164(3), 221–

235.

Henry, H., Naujokas, M. F., Attanayake, C., Basta, N. T., Cheng, Z., Hettiarachchi, G. M., … Scheckel, K. G. (2015). Bioavailability-Based In Situ Remediation To Meet Future Lead (Pb) Standards in Urban Soils and Gardens. *Environmental Science & Technology*, 49(15), 8948–8958.

Intawongse, M., & Dean, J. R. (2006). Uptake of heavy metals by vegetable plants grown on contaminated soil and their bioavailability in the human gastrointestinal tract. *Food Additives and Contaminants*, 23(1), 36–48.

ITRC [Interstate Technology & Regulatory Council]. (2012). Incremental Sampling Methodology. *ISM-1. Washington, D.C.: Interstate Technology & Regulatory Council, Incremental Sampling Methodology Team*. https://www.itrcweb.org/ISM-1.

Jiwan, S. (2011). Effects of Heavy Metals on Soil, Plants, Human Health and Aquatic Life. *International Journal of Research in Chemistry and Environment*, 1(2), 15-21.

Johri, N., Jacquillet, G., & Unwin, R. (2010). Heavy metal poisoning: the effects of cadmium on the kidney. *BioMetals*, *23*(5), 783–792.

Karadaş, C., & Kara, D. (2011). In vitro gastro-intestinal method for the assessment of heavy metal bioavailability in contaminated soils. *Environmental Science and Pollution Research*, 18(4), 620–628.

Kasemodel, M. C., Lima, J. Z., Sakamoto, I. K., Varesche, M. B. A., Trofino, J. C., & Rodrigues, V. G. S. (2016). Soil contamination assessment for Pb, Zn and Cd in a slag disposal area using the integration of geochemical and microbiological data. *Environmental Monitoring and Assessment*, *188*(12).

Khan, S., Farooq, R., Shahbaz, S., Khan, M. A., & Sadique, M. (2009). Health Risk Assessment of Heavy Metals for Population via Consumption of Vegetables. *World Applied Sciences*, 6(12), 1602-1606.

Luo, X.-S., Xue, Y., Wang, Y.-L., Cang, L., Xu, B., & Ding, J. (2015). Source identification and apportionment of heavy metals in urban soil profiles. *Chemosphere*, *127*, 152–157.

Marin, A. R., Pezeshki, S. R., Masscheleyn, P. H., and Choi, H. S. (1993). Effect of dimethylarsinic acid (DMAA) on growth, tissue arsenic and photosynthesis of rice plants. *Journal of Plant Nutrition*, 16(5), 865–880.

Martin, S., & Griswold, W. (2009). Human Health Effects of Heavy Metals. *Environmental Science and Technology Briefs for Citizens*, 15.

Mielkel, H. W., & Reagan, P. L. (1998). Soil Is an Important Pathway of Human Lead Exposure. *Environmental Health Perspectives*, 106, 13.

Moller, K. M., Hartwell, J. G., Simon-Friedt, B. R., Wilson, M. J., & Wickliffe, J. K. (2018). Soil contaminant concentrations at urban agricultural sites in New Orleans, Louisiana: A comparison of two analytical methods. *Journal of Agriculture, Food*

Systems, and Community Development.

Nemati, K., Bakar, N. K. A., Abas, M. R., & Sobhanzadeh, E. (2011). Speciation of heavy metals by modified BCR sequential extraction procedure in different depths of sediments from Sungai Buloh, Selangor, Malaysia. *Journal of Hazardous Materials*.

Nicholls, A. M. and Mal, T. K. (2003). Effects of lead and copper exposure on growth of an invasive weed, Lythrum salicaria L. (Purple Loosestrife). *Ohio Journal of Science*, 103(5), 129–133.

Parker, M. (2018). 1 in 6 children in Savannah's historic district living with high lead levels. http://www.wtoc.com/story/37442306/1-in-6-children-in-savannahs-historic-district-living-with-high-lead-levels/

Piatak, N. M., Parsons, M. B., & Seal, R. R. (2015). Characteristics and environmental aspects of slag: A review. *Applied Geochemistry*, *57*, 236–266.

Rehagen, T. (2013). The Proctor Creek Project. *Atlanta Magazine.* https://www.atlantamagazine.com/2013/proctor-creek-atlanta-epa/

Saleh, H. N., Panahande, M., Yousefi, M., Asghari, F. B., Oliveri Conti, G., Talaee, E., & Mohammadi, A. A. (2018). Carcinogenic and Non-carcinogenic Risk Assessment of Heavy Metals in Groundwater Wells in Neyshabur Plain, Iran. *Biological Trace Element Research*.

Samuel, M. (2017). The Trouble With Atlanta's Proctor Creek. WABE Organization. https://www.wabe.org/the-trouble-with-atlantas-proctor-creek/

Satarug, S., & Moore, M. R. (2004). Adverse Health Effects of Chronic Exposure to Low-Level Cadmium in Foodstuffs and Cigarette Smoke. *Environmental Health Perspectives*, *112*(10), 1099–1103.

Sheldon, A. R. and Menzies, N. W. (2005). The effect of copper toxicity on the growth and root morphology of Rhodes grass (Chloris gayana Knuth.) in resin buffered solution culture. *Plant and Soil*, 278(1-2), 341–349.

Silbergeld, E. K. (1997). Preventing lead poisoning in children. *Annual Review of Public Health*, 18(1), 187–210.

Sun, S.M., Shan, B.Q., & Peng, W.J. (2009). Transformation of inorganic nitrogen in slag-wetland during the start-up period. *Environ. Sci*, 30 (5), 1357–1361.

U.S. Department of Housing and Urban Development. (2006) Lead. *U.S. Department of Housing and Urban Development*. https://www.hud.gov/sites/documents/DOC_11875.PDF

U.S. Environmental Protection Agency. (2015). Proctor Creek Watershed Monitoring: First Quarterly Sampling Event Final Report. *U.S. Environmental Protection Agency Region 4.*

U.S. Environmental Protection Agency. (2016). Proctor Creek Watershed Monitoring: Second Quarterly Sampling Event Final Report. *U.S. Environmental Protection*

Agency Region 4.

U.S. Environmental Protection Agency. (2018). Urban Waters and the Proctor Creek Watershed/Atlanta (Georgia). *U.S. Environmental Protection Agency.* https://www.epa.gov/urbanwaterspartners/urban-waters-and-proctor-creek-waters hedatlanta-georgia

Walker, D. J., Clemente, R., Roig, A., & Bernal, M. P. (2003). The effects of soil amendments on heavy metal bioavailability in two contaminated Mediterranean soils. *Environmental Pollution*, 122(2), 303–312.

Wuana, R. A., & Okieimen, F. E. (2011). Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecology*, 2011, 1–20.

8. Tables and Figures

Table 1: Descriptive statistics of heavy metal concentration levels in all 281 soil samples collected from 15 sample sites.

Metal	EPA Standard[1]	UGA Standard[2]	Min	Max	Mean	Median	SD	Skewness
Lead (Pb)	400	75	LOD[5]	1263	173	76	232	2.4
Arsenic (As)	68	20	LOD	127	12.4	7.15	16.2	3.6
Cadmium (Cd)	210	2	LOD	55.3	13.6	9.2	10.9	1.1
Barium (Ba)	46000	1000	LOD	22804	2098	393	4585	2.7
Calcium (Ca)	NA[3]	NA	LOD	33816	9414	8263	7579	0.7
Chromium (Cr)	30[4]	100	LOD	148	62.3	64.6	24.1	0.04
Copper (Cu)	9400	100	LOD	1002	51.2	43.0	64.8	11.6
Iron (Fe)	160000	NA	5889	69623	25496	23292	10759	1.0
Potassium (K)	NA	NA	LOD	31265	15839	15168	6687	-0.06
Manganese (Mn)	5500	NA	104	1406	518	503	176	1.1
Nickel (Ni)	2500	50	LOD	154	35.9	31.7	19.9	1.5
Sulfur (S)	NA	NA	LOD	7659	868	760	828	3.1
Titanium (Ti)	430000	NA	376	6779	3859	3974	974	-0.2
Zinc (Zn)	70000	100	42.9	1238	234	157	203	2.5

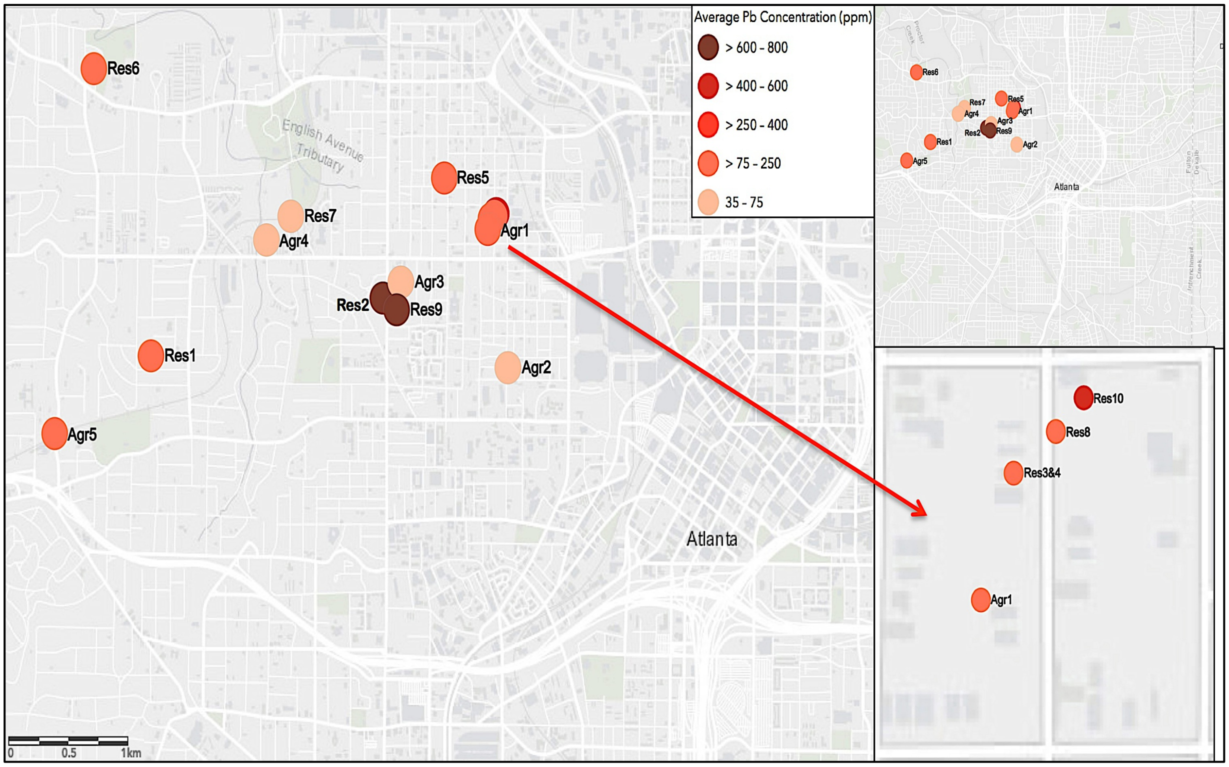
1. EPA Standard refers to EPA regional screening level (RSL) for residential soil.
2. UGA Standard refers to risk reduction standards for agricultural soil required by the University of Georgia.
3. NA means there is no standard for this specific metal.
4. The EPA Standard is specific for Cr(VI). The measurements presented are total Cr.
5. LOD refers to the detected level of heavy metal concentration is below the limit of detection.

*All results in parts per million (ppm).

Table 2: Pearson correlation coefficients of heavy metal soil concentrations and detected eight bioavailable heavy metal concentrations in mimicked gastrointestinal environment. Coefficients higher than 0.5 are highlighted in red.

	Intestine	Stomach	Total
Pb	0.77	0.66	0.70
As	0.69	0.41	0.56
Cd	0.25	0.55	0.53
Ba	0.28	0.11	0.12
Cr	0.63	-0.030	0.27
Mn	-0.035	0.31	0.28
Ni	0.095	-0.13	-0.024
Zn	0.68	0.55	0.57

Figure 1a: Average Pb Soil Concentration at Each Site (UGA Standard 75 ppm & EPA Standard 400 ppm)



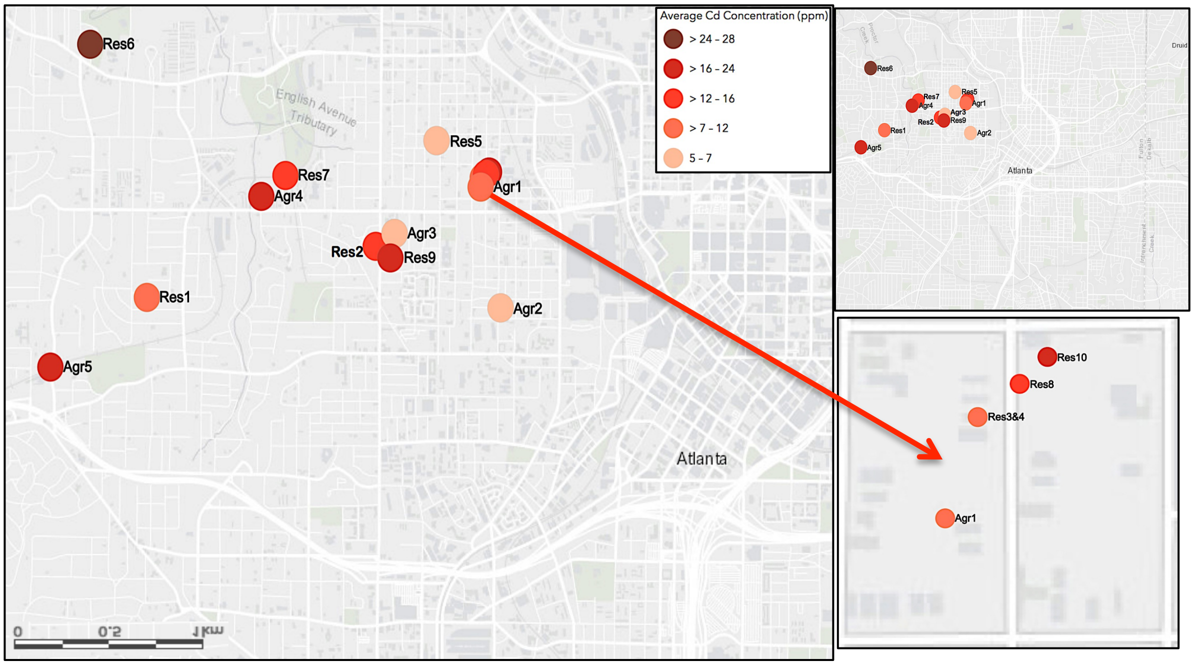
* Res refers to residential gardens in private homes.

* Agr refers to agricultural gardens owned by the community members.

* EPA Standard refers to EPA regional screening level (RSL) for residential soil.

* UGA Standard refers to risk reduction standards for agricultural soil required by the University of Georgia.

Figure 1b: Average Cd Soil Concentration at Each Site (UGA Standard 2 ppm & EPA Standard 210 ppm)



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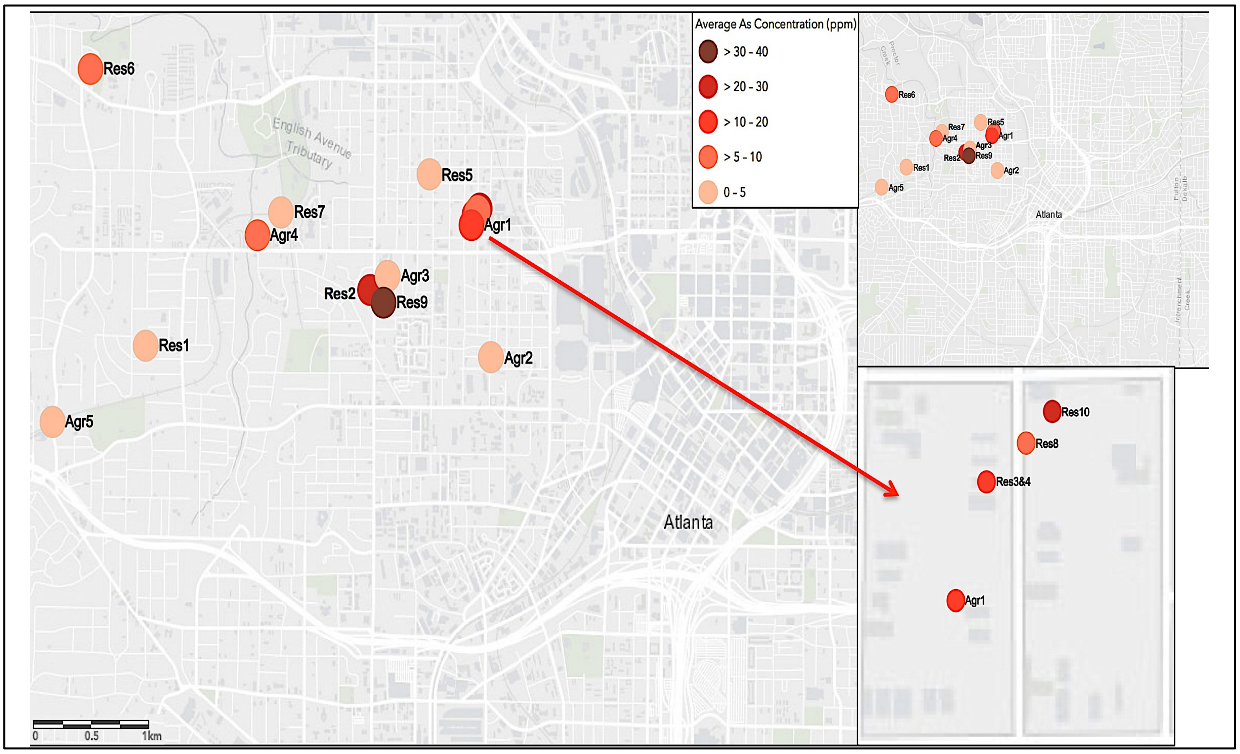
* UGA Standard refers to risk reduction standards for agricultural soil required by the University of Georgia.

Figure 1c: Average As Soil Concentration at Each Site (UGA Standard 20 ppm & EPA Standard 68 ppm)



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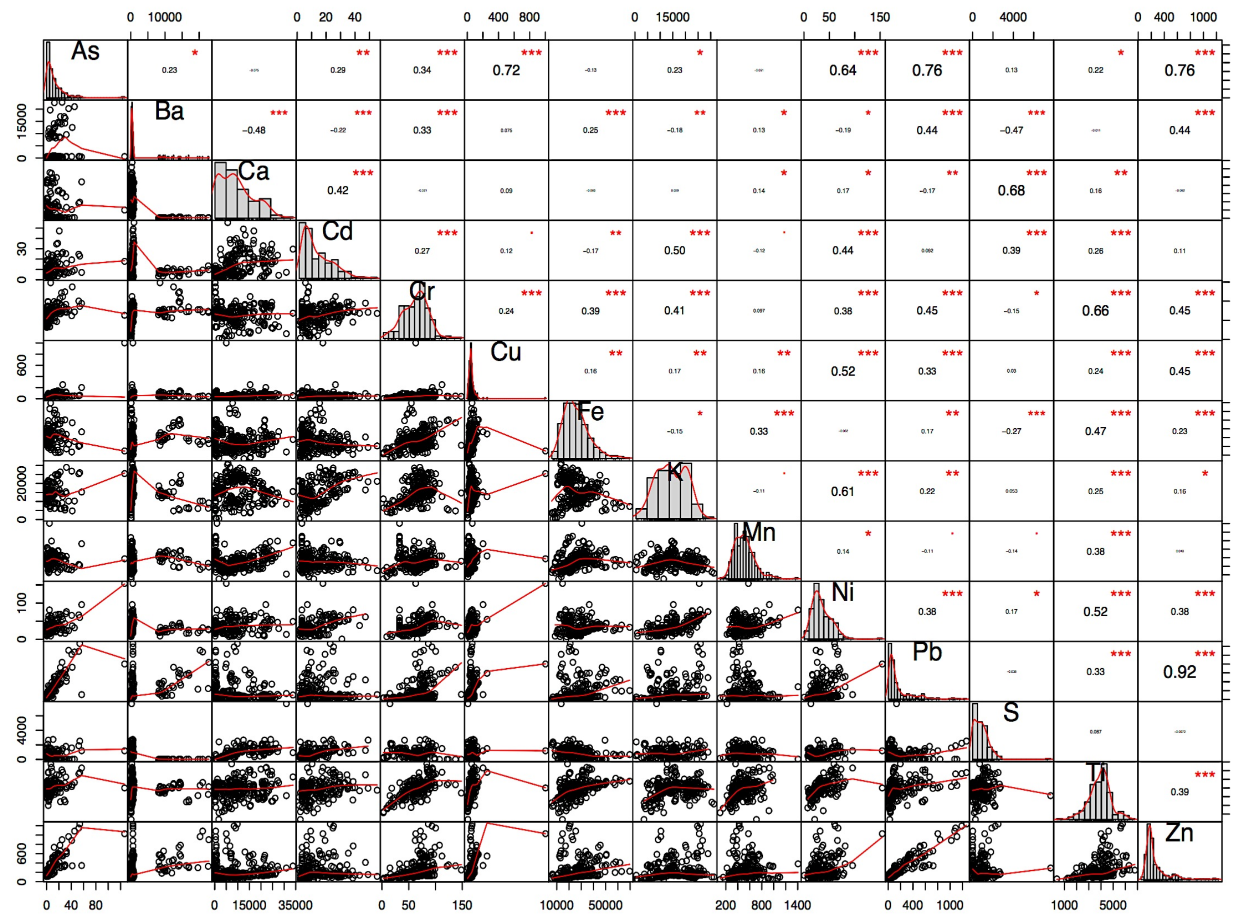
* UGA Standard refers to risk reduction standards for agricultural soil required by the University of Georgia.

Figure 2: Correlation matrices among 14 metals from 281 soil samples.



* The distribution of each heavy metal is shown on the diagonal
* On the bottom of the diagonal is the bivariate scatter plots with a fitted line.
* On the top of the diagonal is the value of the correlation plus the significance level as stars
* Each significance level is associated to a symbol. P-value < 0.0001 = "***"; P-value <0.01 = "**"; p-value < 0.05 = "*"; p-value < 0.1 = "." and p-value <1 = "".

Figure 3: Stomach and intestinal heavy metal bioavailability as a percentage of heavy metal soil concentrations. Soil samples were separated into three different groups depending on soil Pb concentrations, analyzed using XRF. L refers to the first group and was soil Pb concentrations ranging from 200 ppm to 500 ppm; M refers to the second group and was soil Pb concentrations ranging from 500 ppm to 700 ppm; and H refers to the third group and was soil Pb concentrations ranging from 700 ppm to 1000 ppm.

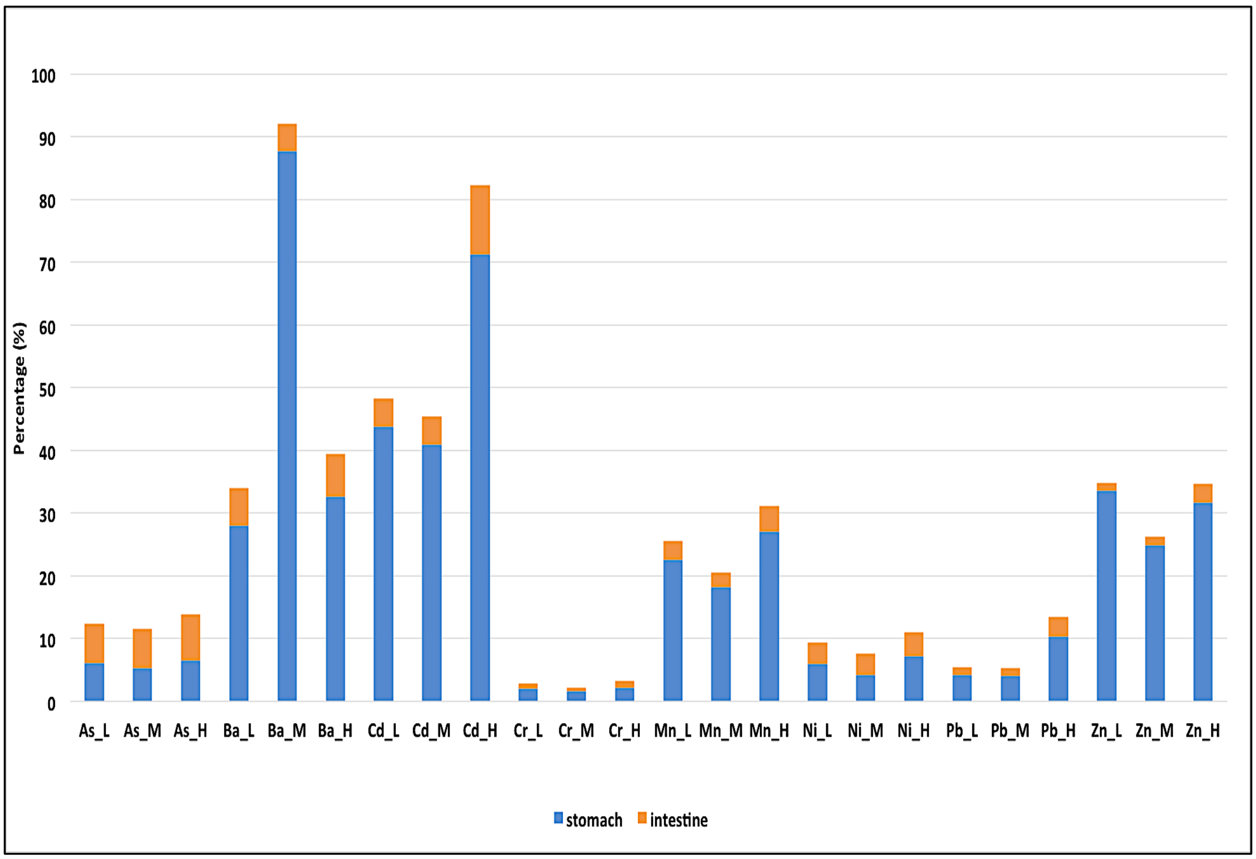
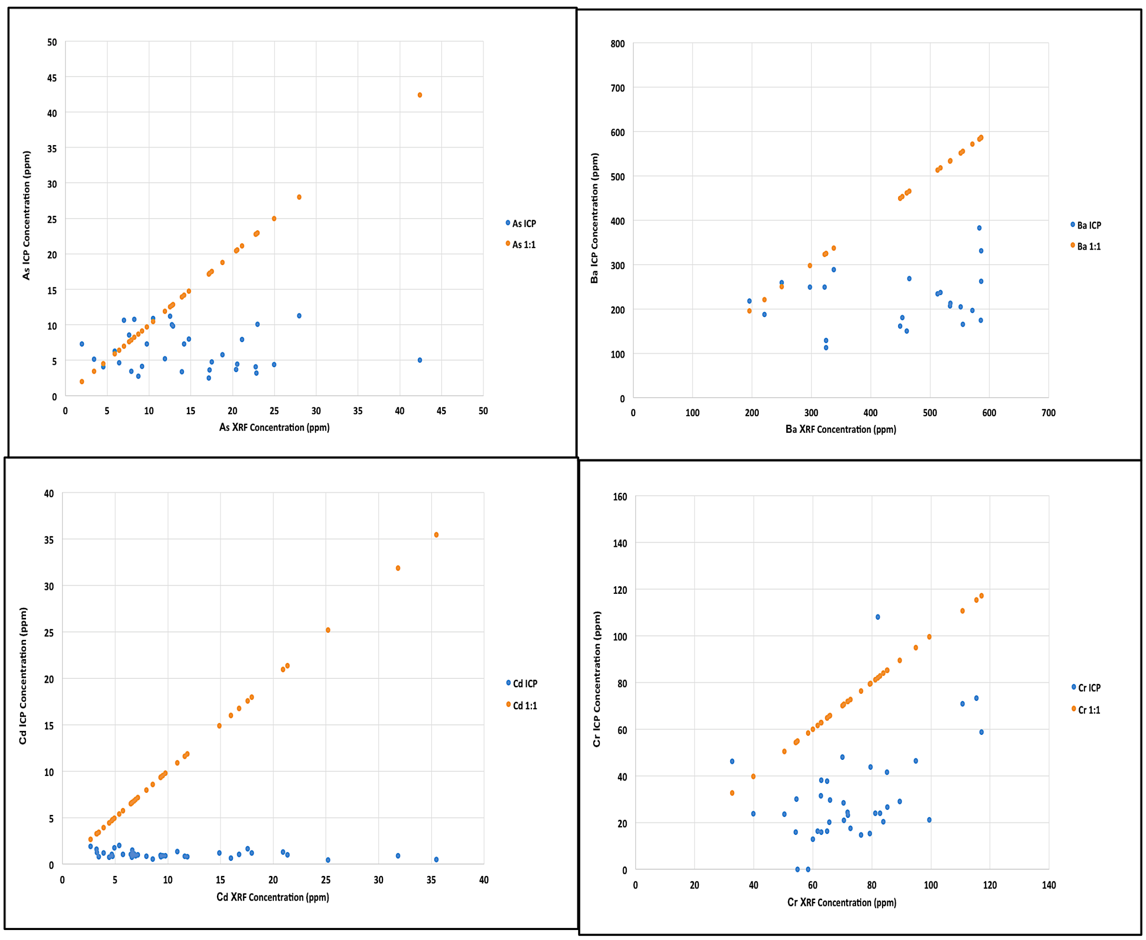
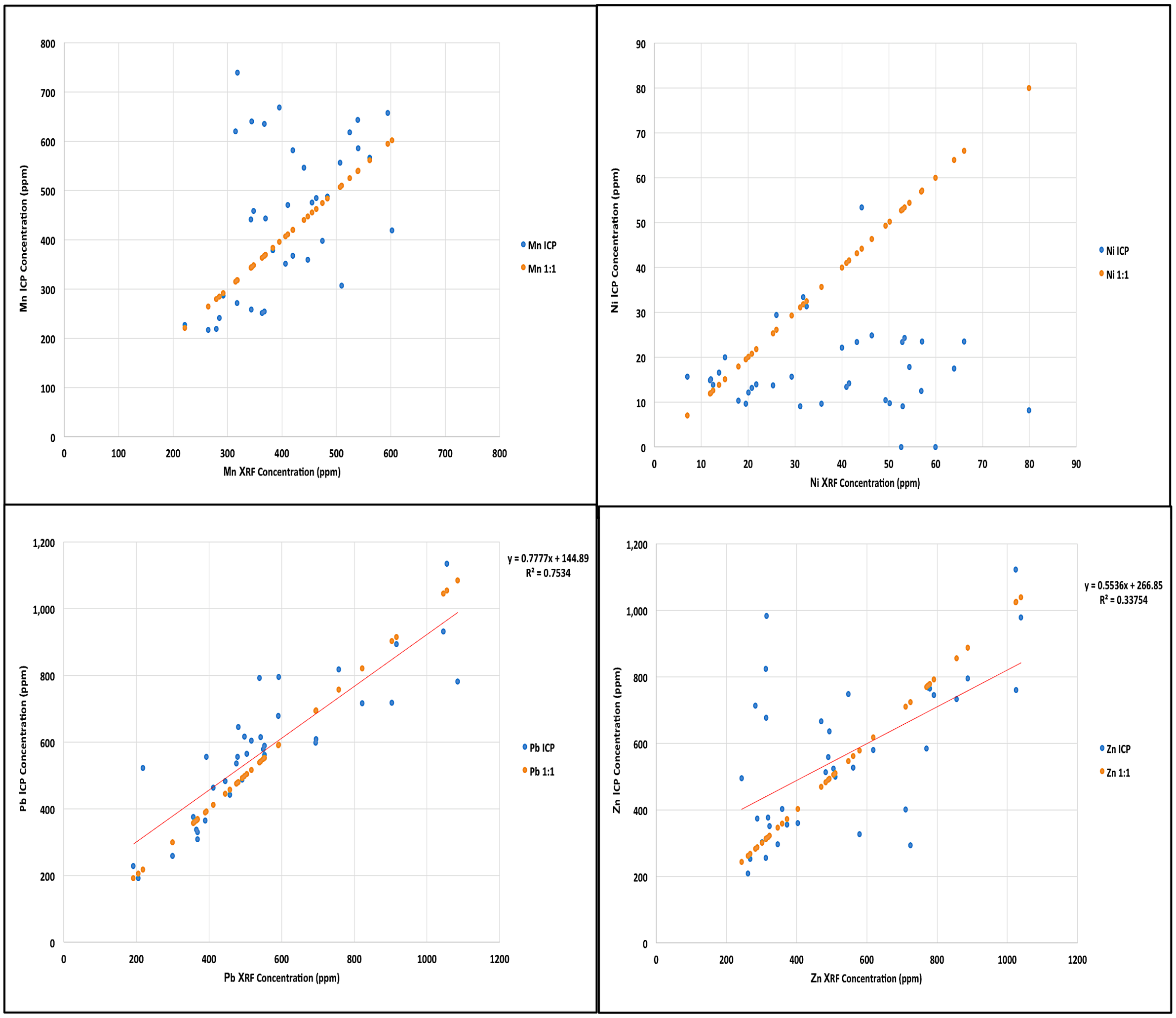


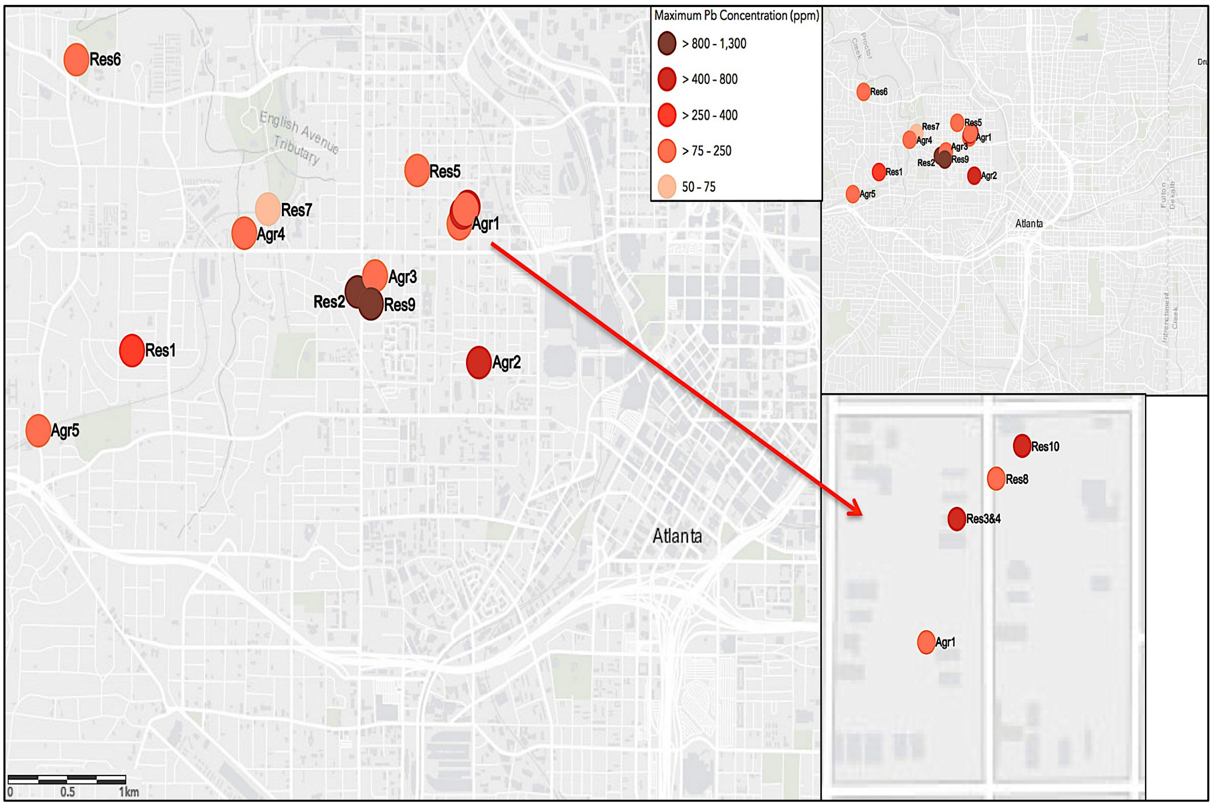
Figure 4: Scatter plots to state the differences between XRF and ICP for eight different bioavailable metals.




Mn ICP Concentration (ppm)
Mn XRF Concentration (ppm)
Mn ICP
Mn 1:1
Ni ICP Concentration (ppm)
Ni XRF Concentration (ppm)
Ni ICP
Ni 1:1
y = 0.7777x + 144.89
R² = 0.7534
Pb ICP Concentration (ppm)
Pb XRF Concentration (ppm)
Pb ICP
Pb 1:1
y = 0.5536x + 266.85
R² = 0.33754
Zn ICP Concentration (ppm)
Zn XRF Concentration (ppm)
Zn ICP
Zn 1:1

9. Appendices

Figure 1a: Maximum Pb Soil Concentration at Each Site (UGA Standard 75 ppm & EPA Standard 400 ppm)



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* EPA Standard refers to EPA regional screening level (RSL) for residential soil.

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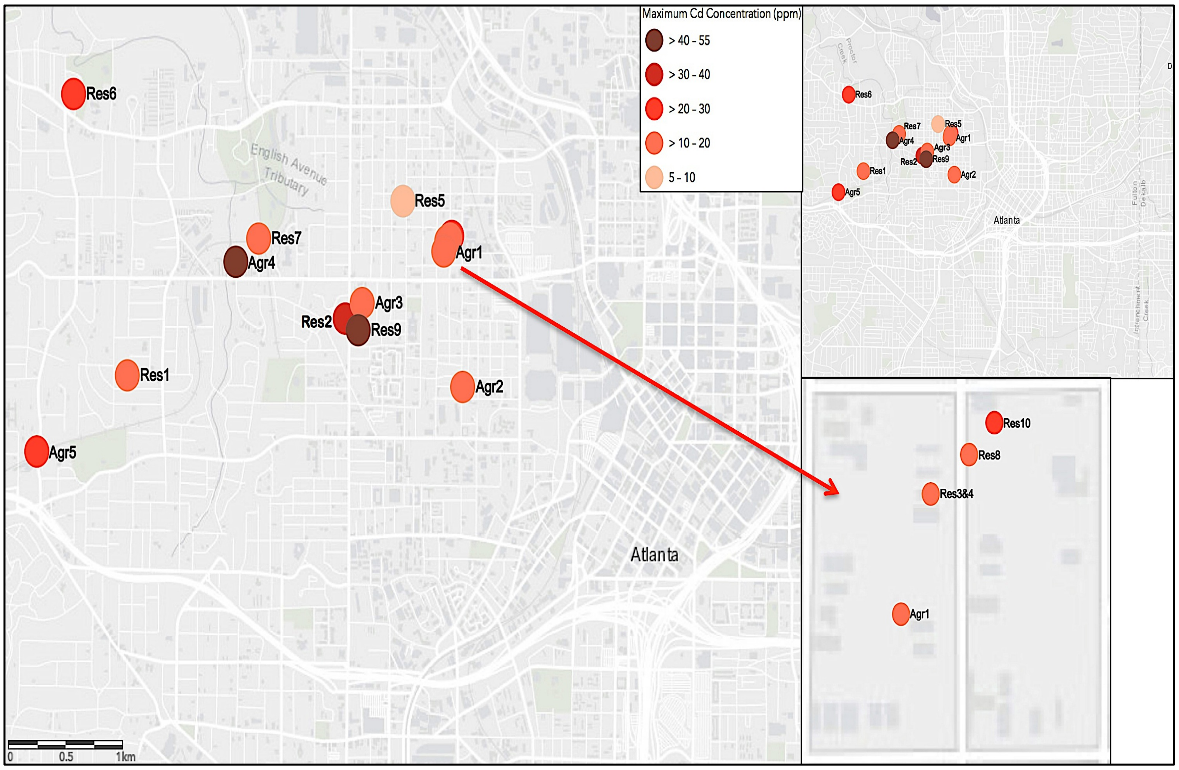
Figure 1b: Maximum Cd Soil Concentration at Each Site (UGA Standard 2 ppm & EPA Standard 210 ppm)



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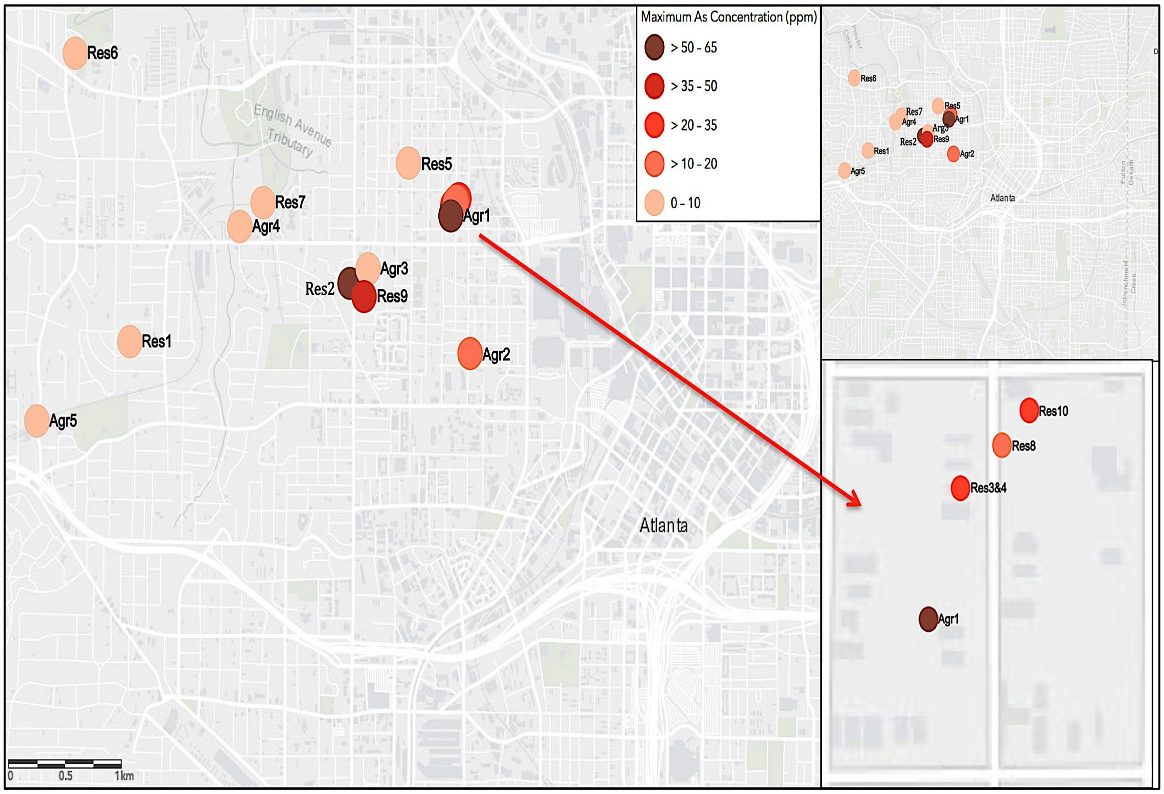
* EPA Standard refers to EPA regional screening level (RSL) for residential soil.

* UGA Standard refers to risk reduction standards for agricultural soil required by the University of Georgia.

Figure 1c: Maximum As Soil Concentration at Each Site (UGA Standard 20 ppm & EPA Standard 68 ppm)



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