The High-Resolution Solution: Phytoremediation and Fine-Scale Mapping of Lead Contaminated Soil at Skidmore College

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Abstract:

Lead is a heavy metal that poses severe health risks, especially to children, at any level of exposure. As a result of its historic use in gas, paints, and infrastructure, lead contaminated soils are widespread. Remediating contaminated areas can be both economically and environmentally costly if not done with careful planning. Like many urban and suburban soils, Skidmore College's ex-community garden contains unsafe levels of lead and should be remediated before any future construction. In order to quantify the extent of the contamination, we grid sampled the site at two depths (0-10 cm and 10-20 cm). The average concentration of lead was similar at both depths (630 ppm at 0-10 cm and 629 ppm at 10-20 cm) with the highest concentration exceeding 3,000 ppm. We recommend high-resolution mapping and selective excavation coupled with soil replacement and biostabilization as cost-effective alternatives to indiscriminate bulk excavation. We estimate that *a priori* sampling with selective remediation could save Skidmore over $100,000 compared to conventional remediation, while mitigating the harmful environmental impacts associated with soil removal and treatment. Further, this technique could be used to reduce costs of other small-scale lead remediation projects.

Introduction:

535,000 children in the United States aged 1 to 5 years have blood lead levels high enough to damage their health (CDC, 2019). When the body absorbs lead, it is stored in the bones, tissue, and blood where it accumulates and leads to a variety of adverse effects on human health. Thus, no level of lead exposure is safe (WHO, 2019). Short-term lead exposure symptoms include abdominal pain, constipation, lethargy, headache, irritability, loss of appetite, memory loss, and pain or tingling in the hands or feet. These symptoms are often mistakenly diagnosed as common ailments, leading to difficulty diagnosing lead exposure. Lead poisoning is a concern for those who experience long-term lead exposure, and can result in depression, gastrointestinal illness, and loss of short-term memory. Additionally, long-term exposure can lead to an increased risk for high blood pressure, heart disease, kidney disease, and reduced fertility (CDC, 2019).

Lead is found naturally within Earth's crust and has become a significant public health concern due to its past widespread use and high level of toxicity. Lead was a component of conventional household paints, pipes, and gasoline from the 1920s until the 1970s when it was determined to be a threat to public health (Lewis, 2016). Even though lead is no longer used in commercial products, its impact remains, due to contamination of homes, gardens, and industrial sites. This contamination results in lead exposure via the inhalation of lead particles when working with contaminated paint or burning of materials containing lead, the ingestion of dust and water which has come into contact with leaded materials, and the ingestion of food which was grown or stored in lead-contaminated areas (WHO, 2019).

The developing bodies of children are more profoundly affected by lead poisoning, and they are also more likely to be exposed. Infants routinely use their mouths to explore the environment around them, which can be dangerous in households that still contain lead paint. Old toys and toys from other countries may contain lead as well (Stanford, 2019). Additionally, lead tastes sweet, and young children may be tempted to eat paint chips (Mielke, 1999). Lead is also more easily absorbed into cells by children than adults, and children who are exposed to high levels of lead can be left with brain damage, among other life-threatening/altering illnesses (Stanford, 2019). Children in low-income areas are more likely to be at risk of lead-exposure than children in more affluent areas (Aelion et al., 2012).

A significant pathway of exposure for children and adults are soils which contain lead from underground pipes or paint chips (CDC, 2019). Lead in soil is difficult to detect without prior knowledge of contamination. Gardens and recreational areas whose soils contain lead could become major health issues. High-density urban areas with older houses, where most low-income minorities live, are at the highest risk of lead-contamination, making lead removal particularly important in these areas (McClintock, 2012). Excavating, transporting, and safely disposing of these soils is often expensive and not a viable option for low-income families.

There are several conventional remediation methods for lead-contaminated soil. Extraction involves removing soil from the contaminated site (ex situ) and treating it with a washing solution and mechanical agitation (soil washing), or using acids to mobilize lead for easier recovery (acid leaching). Another conventional process is solidification/stabilization, in which contaminated soil is mixed with a binding agent and water to minimize potential migration on site. Vitrification, another in situ method, involves converting soils into unreactive glass and crystalline materials by thermal treatment (EPA, 1991).

These three methods are effective at removing lead from soil under certain conditions, but there are serious limitations associated with each. Extraction produces aqueous waste streams and fine particles that require subsequent treatment. Solidification/stabilization increases the volume of treated material by adding reagents, does not treat organics, and presents difficulties in uniform mixing and treatment in-situ. Vitrification is energy intensive, can lead to harmful volatiles, and requires special attention to ensure an impermeable cap has formed (EPA, 1991). These strategies are costly and often detrimental to soil health.

Phytoremediation, an alternative remediation practice, is a growing area of study that exists under the umbrella of bioremediation: the use of living organisms to degrade environmental contaminants into less toxic forms. Specifically, phytoremediation is vegetation-based remediation whereby plants accumulate, immobilize and transform contaminants in soil and water (Vidali, 2001). Plants naturally take up essential metal ions for growth and development. When plants take up unnecessary heavy metal ions, they keep themselves safe by immobilizing them in root and cell walls. Taking advantage of this tolerance to transport and concentrate contaminants from the soil into above-ground shoots is called phytoextraction (Garbisu and Alkorta, 2001). Phytostabilization is another form of phytoremediation that uses roots and rhizospheres to hold contaminants in place to prevent leaching. This strategy requires less effort, but does not allow sequestered lead to be removed from the site (Bidar et al., 2009).

One of the largest advantages to phytoremediation over conventional remediation is the total costs. Conventional in-situ methods of remediation are costly, and with ex-situ methods are even more so, with average costs rising every year (Cunningham et al., 1997, Wan et al., 2016). Additionally, planting flowers as opposed to paving over a large area of land can be more easily accepted by communities (Vidali, 2001). For example, the traditionally remediated Niagra Mohawk Power Corporation Superfund site in Saratoga Springs has been a dull and vacant 7 acre plot for decades, an upsetting stain in an otherwise green area (EPA, 2019). Phytoremediation is also favorable for the value of biomass in secondary markets and the feasibility of large area remediation.

The efficacy of phytoremediation largely depends on the quality of the soil being remediated and the bioaccumulating plant. The ideal plant should be tolerant to high lead levels, accumulate lead in its harvestable parts, have a rapid growth rate, produce a high biomass in the field, and have a profuse root system (Garbisu and Alkorta, 2001). It is also beneficial if the plants used are native to the contaminated area. Corn (*Zea mays)*, a tall grass native to the Americas, is an effective accumulator of lead contaminated soils (Mojiri, 2011). Other lead bioaccumulators include several plants of the *Brassica* genus, the sunflower (*Helianthus annuus* L.), *Agrostis capillaris,* several poplar species, *Triticum vulgare,* and *Oryza sativa* L (Tangahu et al., 2011). Several of these plants require the addition of chelates, compounds that bind to a central metal and make them water-soluble. In this state, heavy metals like lead can be taken in by transpiration. Chelates, however, mobilize metal atoms which may leach into surrounding groundwater.

Skidmore College established its first community garden in April 2009 on a plot of land adjacent to the Colton Alumni House. In August, 2013, an analysis of the garden soil indicated that lead levels were 139ppm in the inner zone of the garden, and 2365ppm in the outer zone. The EPA standard for play areas is anything below 400ppm, and for non-play areas, anything below 1200ppm (ATSDR, 2020). As a result, the community garden was relocated, and the original plot of land was covered with a layer of sod (Rogers, personal communication, 2019).

Space is a valuable commodity at Skidmore College. The swing space used to house science facilities while Skidmore's new Center for Integrated Sciences building is being constructed was initially estimated to take up 32,000 square feet, and required 40,000 square feet deforestation of Skidmore's North Woods. Due to student protests, the president approved recommendations for a two story swing space instead, but deforestation of the northwoods was still a necessary measure for its construction (Skidmore College, 2019). As more space is needed for additional buildings, it is probable that the plot of land on which the original community garden was located will eventually be used for construction.

Construction in general is a source of air pollution. As heavy construction equipment creates particulate matter at diameters of 10 μm or less, which are respirable and harmful to human health and the natural environment (Jung et al., 2019). Blasting to remove rock and excavate the earth has been necessary in previous Skidmore construction projects (Skidmore, 2019). Blasting is also an activity that puts workers at a high risk of lead exposure (OSHA, 2004), We expect that construction on the ex-community garden lot could mobilize lead from the contaminated soil, posing a potential health risk to construction workers and the wider Saratoga Springs community. Phytoremediation of lead is slow, but conventional remediation can be costly; so it is imperative that the Skidmore administrative staff consider a plan for lead-removal that is both timely and cost-effective. Here we examine the distribution and concentration of lead in the ex-community garden's soil and evaluate the costs and practicality of a range of potential remediation approaches. We predict that an uneven distribution of lead in our site will demonstrate that fine-scale sampling coupled with a hybrid remediation approach will reduce overall abatement cost.

A note on COVID-19 in the Spring of 2020

We initially planned to also compare the relative efficacy of sunflower, brown mustard, and corn plants as phytoextractors in Skidmore's greenhouse. We used soil treated with lead acetate and a citric acid chelator. We replicated the growth conditions of the garden plot, and used soil from the plot and the SAIL facility to analyze the amount of lead remediated by each plant. Due to the spread of COVID-19 sending us home, we were not able to complete the comparison of phytoextractors, and instead compared plants using past research.

Case Studies:

Indiana Bridges Case Study (Banks et al., 2005)
Challenge: The Indiana Department of Transportation identified several sites with lead contamination. The lead originated in the paint of nearby highway bridges. **Action**: In an attempt to bypass potentially expensive and logistically problematic conventional solutions, the Joint Transportation Research Program tested other techniques in situ. They planted sunflowers at some sites and added soluble phosphate at others. **Outcomes**: Phytoremediation was not successful due to growing difficulties and sunflowers' lack of affinity for lead. Adding phosphate to immobilize Pb and reduce its bioaccessibility was far more effective. Much less expensive than landfilling or soil extraction, the research group's final recommendation was incorporating phosphate to a depth of 5 cm in contaminated

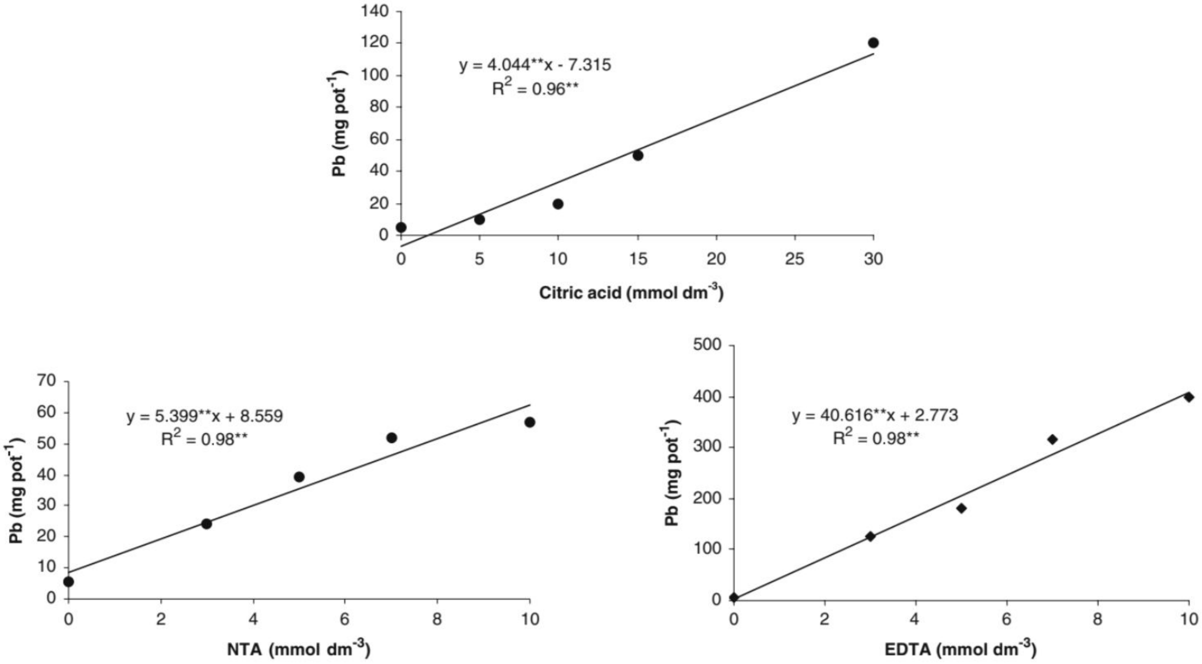
areas. The general lack of lead severity was a contributing factor to their recommendation.

Battery Recycling Plant Study (de Araújo et al., 2010)

Challenge: Researchers collected soil from an automobile-battery recycling facility at depths of 0-20 cm and found a homogenized lead content of 1,544 ppm.

Action: Researchers planted maize in pots and tested the efficacy of biodegradable chelates NTA (nitrilotriacetic acid) and citric acid, as well as conventionally used chelate EDTA (ethylenediaminetetraacetic acid).

Outcome: The addition of EDTA solubilized more Pb than other chelates, but resulted in solubilized lead that far exceeded the plants' uptake ability, resulting in leaching from the rhizosphere. Citric acid addition resulted in the least solubilization, but still caused a 19-fold increase in lead uptake compared to the control when using 30 mmol/dm^3. de Araújo et al concluded by emphasizing the safety of citric acid and the efficacy of maize as a hyperaccumulator.



Regressions between the net removal of Pb (mg pot^{-1}) by maize shoots and crescent doses of EDTA, Citric Acid, and NTA added to the soil.

Edenspace Systems Case Studies (Henry, 2000)

Despite the potential utility of phytoremediation, studies tend to occur more frequently in the lab then the field, and commercial access to phytoremediation is limited. The 1990s saw some of the first commercial phytoremediation companies, including a company called Phytotech. The company later collapsed due to a lack of government funding and investors, but it later sold its equipment to a company called Edenspace, which has done some work with commercial phytoremediation, conducting several studies in the field that also served as remediation projects of contaminated areas.

Bayonne, NJ

Challenge: The first study took place in 1996 at a lead-contaminated industrial site in Bayonne, NJ, polluted by cable manufacturing operations.

Action: Researchers used *Brassica juncea* (Indian mustard) and EDTA as a chelating agent at 2 mmol/kg. Three crops were grown for 6 weeks before harvesting.

Outcome: Surface level soils dropped from 2,300 to 420 mg/kg lead, and subsurface soils dropped from 1,280 to 992 mg/kg. Another in Dorchester, ME saw subsurface lead levels that increased slightly from 538 to 671 mg/kg (likely due to leaching from surface soils), but dropped from 984 to 644 mg/kg on the surface. This study took place in a heavily-populated urban residential area, demonstrating how phytoremediation could be used in a variety of locations.

Trenton, NJ

Challenge: Another study took place at a Brownfield site in Trenton, NJ where soil had been contaminated by the manufacturing of lead acid batteries.

Action: Again, researchers used *Brassica juncea* and EDTA as a chelating agent. The crop was grown for 6 weeks over 4,500 sq. ft.

Outcome: Surface lead dropped from 429 to 373 mg/kg, and subsurface dropped from 600 to 539 mg/kg, showing less efficacy than Bayonne.

Simsbury, CT

Challenge: A 2.35 acres of an open burn/open detonation area with lead concentrations ranged from 125-5,000 mg/kg.

Action: Researchers used *Brassica juncea* and *Helianthus annus* (Sunflower) and unspecified soil amendments to increase lead mobility.

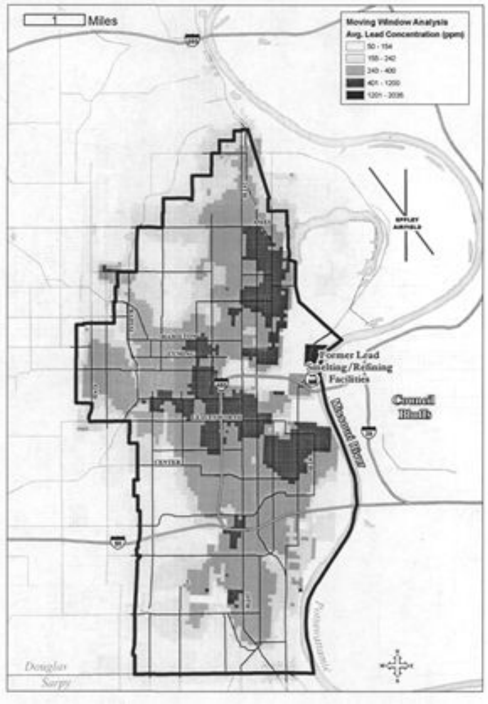
Outcome: Total average soil lead levels dropped from 635 to 478 mg/kg, with plants taking up an average of 1000 mg/kg. Above all, these case studies demonstrate the versatility of phytoremediation at a variety of contaminated sites.

Omaha Lead Superfund Site (EPA, 2020)

Challenge: For over a century, Aaron Ferer and Sons Company ran a lead refinery in downtown Omaha, Nebraska. Later, Gould Electronics operated a lead battery recycling plant nearby. Lead particles entered the air through smokestacks and were deposited in more than 13,000 residential properties.

Action: The EPA was asked for assistance in March of 1999, and testing of soil, exterior paint, and interior dust was conducted at no expense to the property owner. Properties with lead levels greater than 400 ppm were cleaned by extracting contaminated soil, replacing it with clean backfill, and capping the land with a layer of sod.

Outcome: As of December 2015, the EPA completed its action and 93% of contaminated properties were properly cleaned. Efforts continue to address the contaminated properties where owners did not allow soil tests or cleanup.



Chelators:

Chelators are large organic molecules that metal ions bind to in order to allow for greater uptake by plants. Incorrect doses of chelators can create a toxic environment for plants, resulting in inhibited growth and death if not used in the correct concentration (Hong et al., 2002). Additionally, heavy chelate application can result in subsequent leaching of heavy metals into groundwater. However, insufficient chelate application and there is limited uptake. There are a wide range of chelators, but the most widely used and effective chelator is ETDA (Ovieto, 2003). Its efficacy with many types of metals and its high rate of chelation make it a popular choice for phytoextraction. Due to citric acid's relatively low cost and low environmental impacts we recommend it be used if phytoextraction is the chosen remediation strategy.

Chelate	Pros	Cons
EDTA[1,2]	Most effective chelator	Negatively affect biomass of plants
	Safe for humans and used in chelation therapy	Can lead to groundwater contamination
	Versatile	Poor biodegradability in the environment
		Plays a role in eutrophication
		Toxic to photosynthetic organisms
Citric Acid[1]	Low doses do not affect plant growth	Increases acidity of soil in high doses
	None/Low environmental impacts	Not as effective as EDTA
	Easily accessible	
	Cost effective	
EDDS[3,4]	High biodegradability	Not as effective as Citric Acid
	Residual in soil does not harm future plants	Effective on limited heavy metals
	Metals in leachate are more readily absorbed compared to EDTA	
Oxalic Acid[5]	Relatively small environmental impact	Limited success in research

	No plant toxicity	
	No impact on plant biomass	

Table 1. Pros and cons of synthetic and biodegradable chelates

Hyperaccumulators:

In addition to being well-suited to local climate, plants selected for phytoremediation should reflect the contamination concentrations they will address, and their rooting depth should be appropriate to reach soil contamination. Like chelators, different plants are more effective at targeting specific contaminants. Further, some plants are more tolerant to chelators and contamination than others.

Species	Root depth	Use with citric acid
Corn (zea mays)	5-6 ft bulk, up to 8 ft[6]	40 mmol per kg was very effective[1]
Indian Mustard (brassica juncea)	~3-4 ft[7]	Works with heavy metals (Pb not tested)[1]
Sunflower (helianthus annuus)	1.5 ft bulk, 5 ft tap[8]	Higher Pb concentrations than control, safer than EDTA and DTPA due to less leaching[9]
Rapeseed (brassica napus)	4.59 feet[10]	Used for cadmium, not Pb[11]
White cabbage (brassica oleracea)	1.5-3 feet[12]	Has not been used with chelates

Table 2. Hyperaccumulators and their use with citric acid chelator

Methods:

<u>Site description:</u>

The contaminated plot is located at 815 North Broadway in Saratoga Springs, New York (43°05'43.7"N 73°46'44.3"W). The plot is 202.5 m^2 and contains loamy soil with a three to eight percent slope (USDA, 2020) (Figure 1).

Figure 1. Location of Study Site

<u>Grid:</u>

We established a 22.5 x 22.5 meter grid, sampling at 0-10 cm and 10-20 cm, at 2.5 meter intervals throughout. We then used a Geo XH 6000 Trimble unit to mark the corners within a 17-inch error margin (Figure 1).

Figure 2. Study design. Each cell in the grid is 2.5m^2

<u>Soil Sampling and Analysis:</u>

Using the proper safety equipment and a push probe, we divided soil cores into 0-10 cm soil and 10-20 cm soil, and transferred them to the lab for storage at 30℉. We put the soil samples in labeled ziplock bags and stored them in a refrigerator. We filtered all samples with a 2 mm mesh sieve for homogenization and to remove rocks, roots, and large organic material. We then macerated each sample with a mortar and pestle.

Each sample associated with the ex-community garden was digested using 10 mL of pure nitric acid and a microwave digester. We filtered the digested samples and used the Atomic

Absorption Spectrophotometer in the Skidmore SAIL facility to analyze Pb concentration (Sarojam, 2011). We scaled lead concentration to a per gram of dry soil basis.

Remediation Cost Analysis:

We used QGIS to join the lead data with each point on the grid, and visualize the lead distribution over the plot, as well as subdivide the plot into regions of potential remediation for cost analysis. We reached out to soil remediation groups in the Capital Region and collected estimates for excavations, transport, and disposal costs at three different scales: total area excavation, excavation of lead concentrations above 400 ppm, and excavation of lead concentrations above 1200 ppm. Estimates of each stage of remediation were averaged from different soil remediation groups, and represent only approximate values. The processing of a single soil sample was estimated to cost $35 (Midwest Laboratories, Personal Communication, 2020).

Results:

<u>Spatially Referenced Lead Values:</u>
See appendix for lead values.

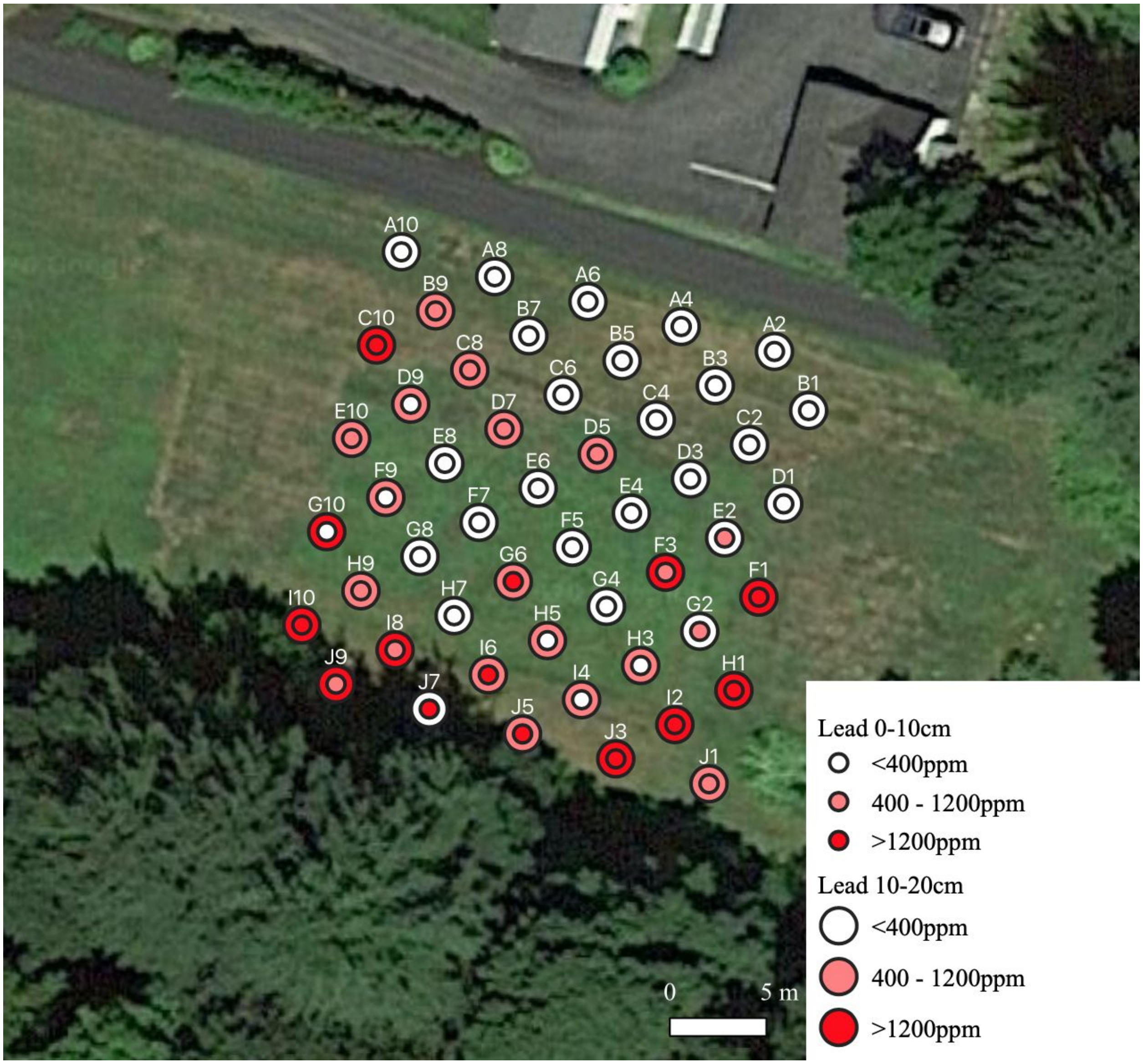


Figure 3. Field characterization of the Pb concentrations (ppm) at Skidmore's ex-community garden at 0-10 cm and 10-20 cm.

The mean soil lead concentration at depths of 0-10 cm was 630 ppm +/- 102 ppm (Mean +/- SE). Mean soil lead concentration at depths of 10-20 cm was 629 ppm +/- 85.6 ppm.

Cost analysis results:

We obtained an estimate from Clean Management Environmental Group and MC Environmental Services for the transportation and disposal of soil. They estimated \$50,250 for 85 m^2 (+/- \$4,750), \$92,000 for 172.5 m^2 (+/- \$7,500), and \$106,250 for 202.5 m^2 (+/- \$8,750) of soil at depths of 20 cm. Only MC Environmental Services could give us an estimate of excavation costs. These were \$25,000 for 85 m^2, \$50,500 for 172.5 m^2, and \$69,000 for 202.5 m^2 of soil at depths of 20 cm.

Discussion and recommendations:

Figure 4. Lead concentrations categorized by EPA standards. Each cell (2.5m^2) represents the highest value at each of its corners and at both depths.

Lead was distributed unevenly throughout the site, with concentrations over 1200 ppm (unsafe levels) appearing more frequently to the south and to the west, and values under 400 ppm (safe for play areas) appearing more frequently to the north (Figure 4).

In blocks of easily removable areas, we divided our map into lead concentrations below 400 ppm, which is safe for play areas by EPA standards, between 400 and 1200 ppm, which is safe for non-play areas by EPA standards, and above 1200 ppm, which is unsafe by EPA standards (Figure 5). These scales represent different magnitudes of remediation for Skidmore College to choose from. If they are planning on using the plot of land for child-related purposes, they can excavate soil to the 400 ppm level, for example. A distinct advantage of fine scale mapping is the ability to tailor remediation to land use.

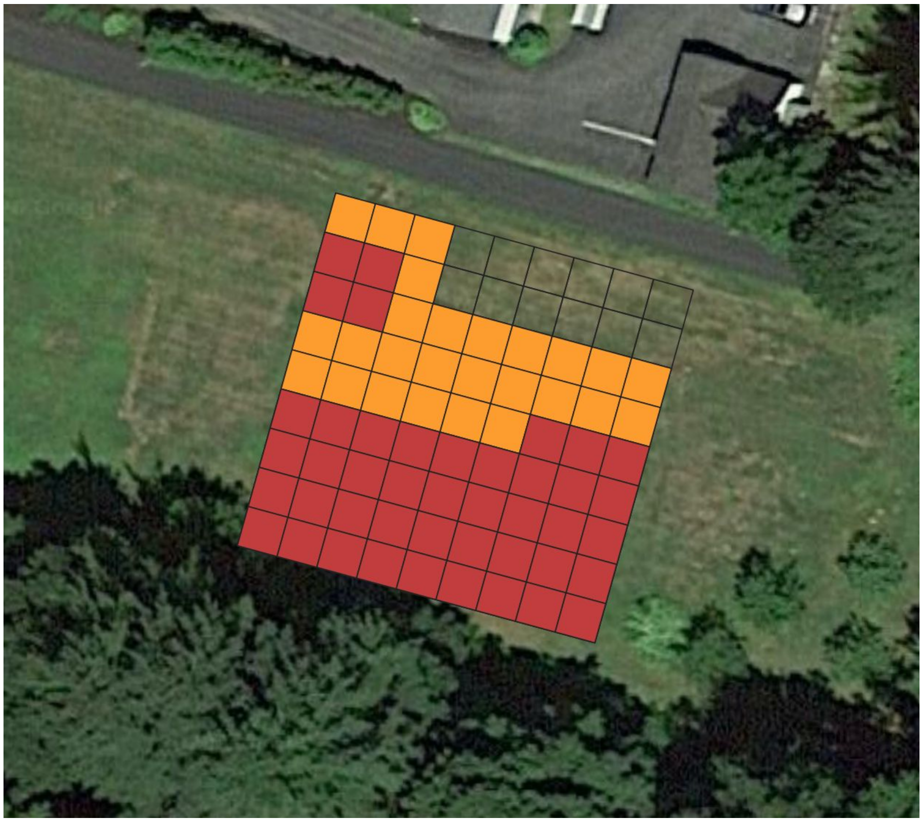


Figure 5. Cost analysis visualized. Red areas represent 17m^3 excavated, and red and orange areas combined represent 34.5m^3 excavated.

When a property owner discovers unsafe levels of lead contamination in their soil, they can approach remediation in different ways (Figure 6). Their first option is to rely on the one sample they have and pay an environmental services group to excavate all of the soil within a fixed area. The costs of this method come from the excavation itself, the transport, and the disposal of the exhumed soil. The landowner incurs additional expenses for purchasing, transporting, and placing clean fill.

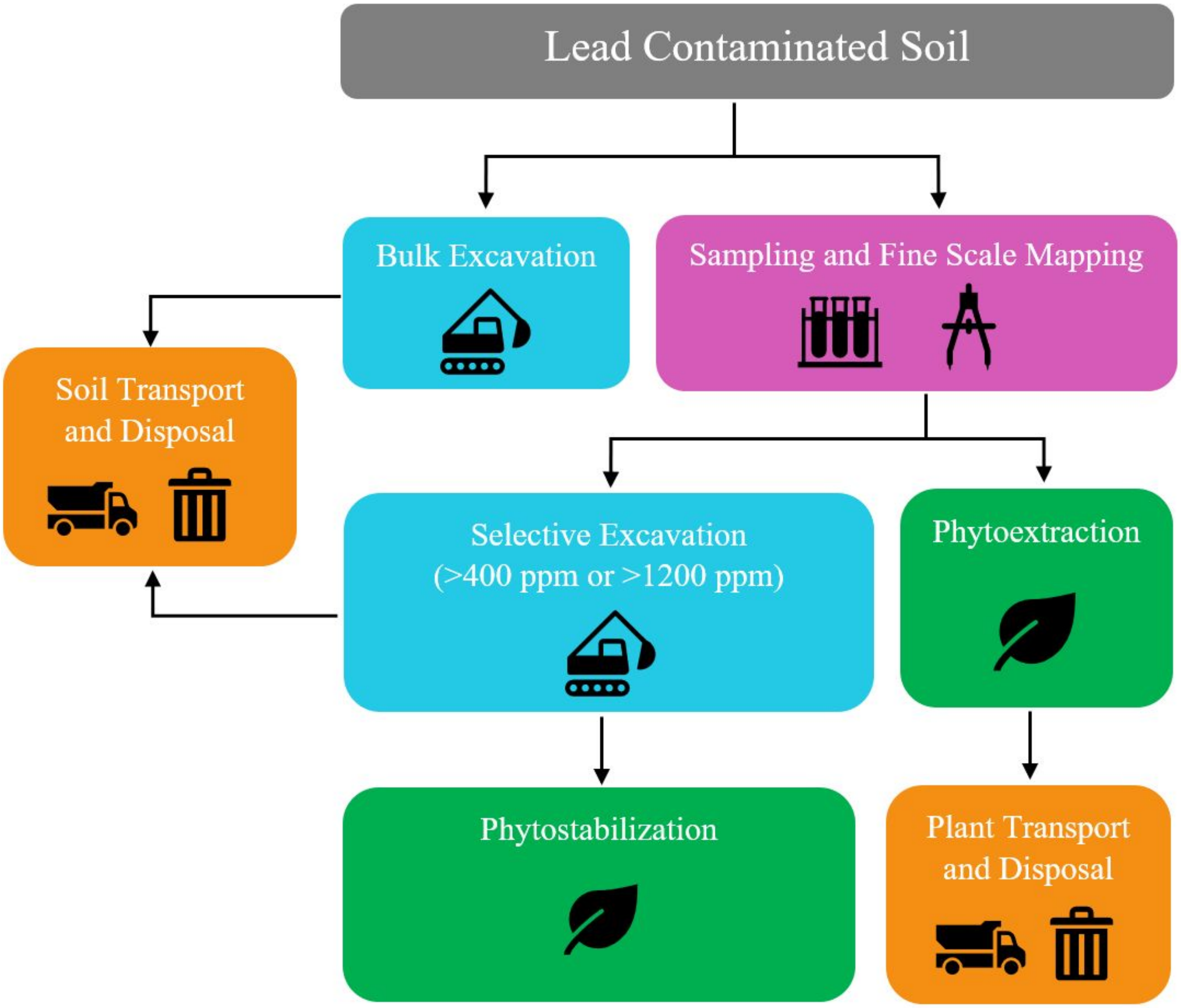


Figure 6. Process diagram for lead contaminated soil remediation.

The property owner's other option is taking soil samples in a grid system and sending them to a lab to create a map of lead concentration. This "fine-scale mapping" comes with the cost of time and lab fees, but presents several advantages to bulk extraction. The property owner has the freedom to decide what level of lead concentration they are comfortable with, whether it be 1200 ppm or 400 ppm, and can exhume only soil with concentrations higher than their chosen value. Less soil reduces excavation, transportation, and disposal cost, as well as the amount of soil needed to refill holes.

Average costs in the literature of in-situ remediation tend to range from \$81 to \$260 per m^3 and up to \$813 for ex-situ processes. Our personal outreach to contractors found extraction costs to average around \$4346.2 per m^3. In comparison, phytoremediation can cost as low as \$37.7 per m^3 (Wan et al., 2016).

Course of Action	Area (m^2)	Volume (m^3)	[Pb] of soil extracted (ppm)	Sampling Costs	Excavation	Transport and disposal	Total Cost
Entire plot excavated	202.5	40.5	>0	\$35.00	\$69,000	\$106,250	\$175,285.00
Sampling and selective extraction (a)	172.5	34.5	>400	\$1,750.00	\$50,500	\$92,000	\$144,250.00
Sampling and selective extraction (b)	85	17	>1200	\$1,750.00	\$25,000	\$50,250	\$77,000.00

Table 3. Cost analysis for Skidmore's three remediation strategies

We present 3 options that would allow Skidmore College to remediate the lead contaminated ex-community garden (Table 3):

1. The most costly option, at $175,285, is for Skidmore is to remediate the entire 202.5 m^2 site. This is unsurprising because it requires the greatest volume of soil excavated, transported, disposed of, and replaced.
2. More than $30,000 dollars less expensive, Skidmore could employ fine scale mapping and remediate 30 m^2 less soil (only the red and orange blocks in Figure 4) and the area could become "play area safe".
3. For $67,000 less than that, Skidmore could remediate only 85 m^2 of soil, leaving any soil with lead concentrations less than 1200 ppm in situ.

Fine-scale mapping will reduce overall cost and put Skidmore College in a position of full control over the remediation process. We recommend Skidmore College include fine-scale mapping when remediating the ex-community garden.

Due to the high lead concentrations in the ex-community garden, we do not recommend phytoextraction as a viable remediation strategy. Similar phytoremediation studies with high lead levels estimate hundreds of years for decontamination (Cheng et al., 2015). Skidmore College is growing quickly, and to have a 202.5 m^2 area of land off-limits for generations would be a heavy burden. However, we still do recommend phytostabilization on the remaining soil once the above threshold areas have been excavated. Lead concentrations of 1200 and 400 ppm can still be hazardous through leaching. Phytostabilization immobilize's heavy metals preventing leaching and airborne transport. Unlike phytoextraction, the best plants for phytostabilization keep the heavy metals in the roots as opposed to the shoots. Due to their Pb tolerance, root storage, and ubiquitous presence in the Northeast region, *Trifolium repense (*white clover) and *Lolium* *perenne* (perennial ryegrass) are both suitable phytostabilizers (Bidar et al., 2009). Lead immobilization can also be accomplished with the addition of phosphate, as in the Indiana Bridges Case study, manure, compost, biochar, clay minerals, and coal fly ash (Palansooriya et al., 2020). Regardless of technique, this tiered approach of physiochemical remediation for quick reduction in contaminant concentration, followed by phytoextraction/immobilization as the final step, is used in many cases of high heavy metal contamination (Alkorta et al., 2010). Phytostabilizers are not reliant on bioavailable heavy metals, so we do not recommend the use of chelators at this stage. Chelators would increase shoot uptake of lead, when the goal of stabilization is to keep heavy metals confined in the rhizosphere or the roots.

Conclusion:

The outcome of our study is relevant to any property owner with lead in their soil. For many, remediation is more a question of cost than safety. Those in low income housing or small organizations, for example, may be inhibited by the substantial expense. Luckily, fine-scale mapping is not reserved solely for organizations with direct access to microwave digesters and atomizers for AAS. Residents can find yard sampling protocol online and mail their samples to private analytical labs and some universities for inexpensive testing (Beresovoy, 2007).

Those living in urban areas are most at risk. Cities contain dense infrastructure where underground lead pipes remain. They were hotspots of vehicle use when lead was used in gasoline, and industrial use before lead was known to be dangerous (Zaleski, 2020). Brand new cases of lead contamination in urban areas appear frequently. Skidmore Capstone students found some Saratoga Springs home gardens had lead concentrations as high as 869 ppm (Lovejoy and Semar, 2015). State health officials found 7 residences in the nearby Spa City with drinking water that exceeded EPA regulations (Campbell, 2017). In 2015, attention was directed towards a former lead smelting site in North Philadelphia. More than 20 years after the area was repurposed, tests revealed a high number of children with elevated blood lead levels (Beeler, 2015). Today, half a million American children between 1 and 5 have concerning blood lead levels. These children belong to lower-income, minority communities and are already at-risk. Considering higher levels of lead exposure are correlated with lower test scores and higher rates of criminal activity, a terrible feedback loop takes form (Zaleski, 2020). Low income communities could benefit from the lower cost of fine-scale mapping, provided the government is not paying for remediation themselves.

Fine-scale mapping is also applicable to larger projects. The Omaha Lead Superfund Site case study illustrates just how long large-scale remediation projects can take. The EPA concluded its involvement with the city after more than 15 years, during which, at-risk children may have been exposed. The sampling method in Omaha divided each residence into quadrants and excavated any quadrant with a lead concentration greater than 800 ppm, or 400 ppm if a child lived there (EPA, 2009). This is more efficient than bulk excavation, but their method could still have been improved if sampling had been increased to map fine-scale concentration variability. Excavation time would have decreased, safe soil would have been saved, and the superfund operation could have been completed sooner.

The next step in our study is to make fine-scale mapping accessible to homeowners and contractors in residential settings. Fine scale soil mapping, as it exists in this study, requires technical expertise precluding widespread use. Accordingly, there is a need for an application that can take sample data, assign them to points on a raster map, and generate a visual similar to our cost analysis (Figure 4), with minimal user input.

By exploiting modern soil mapping techniques, property owners can greatly reduce costs as compared with bulk excavation while achieving similar results. Automating the mapping process would further reduce end user costs, encouraging more remediation and alleviating a common urban pollutant.

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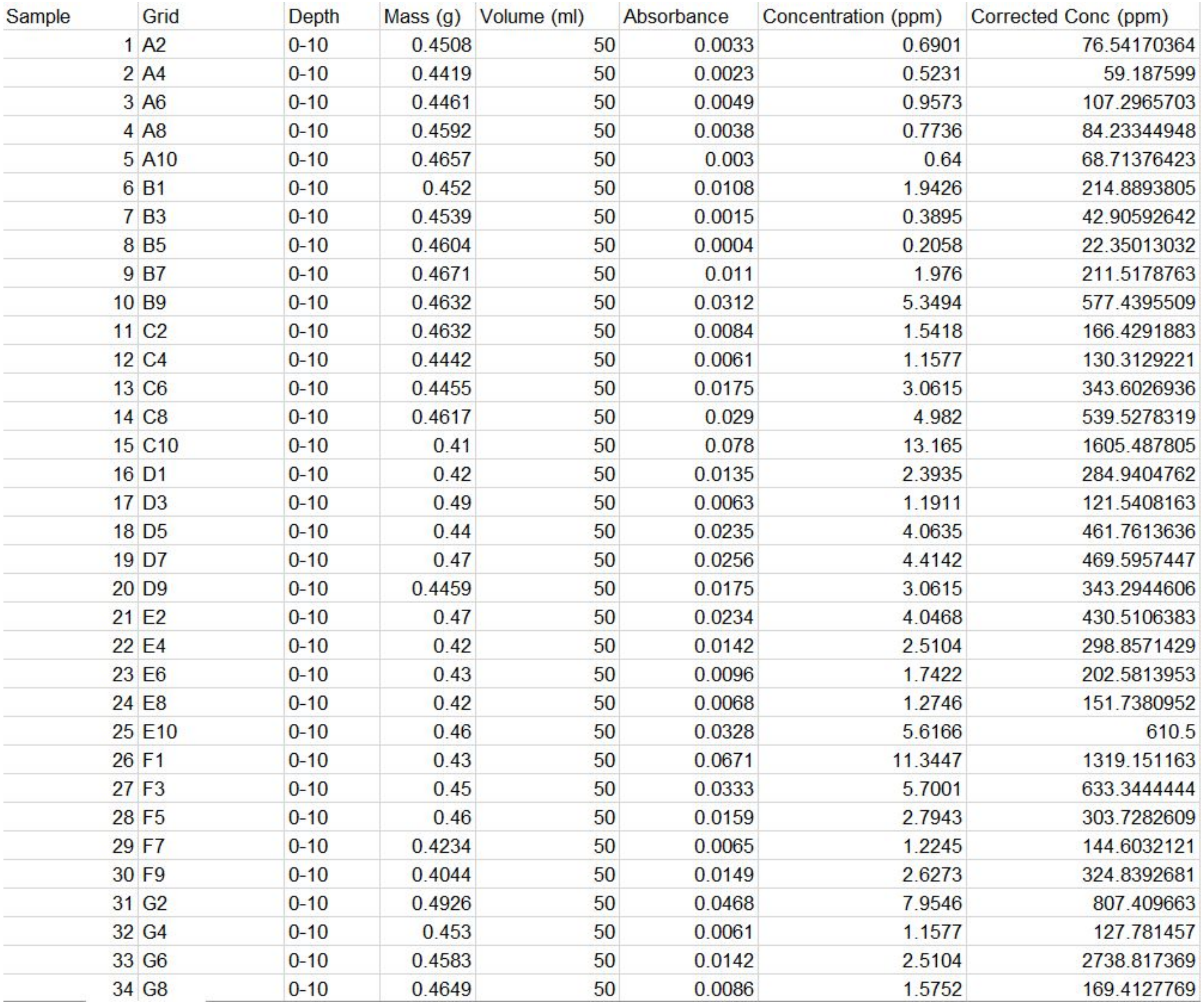
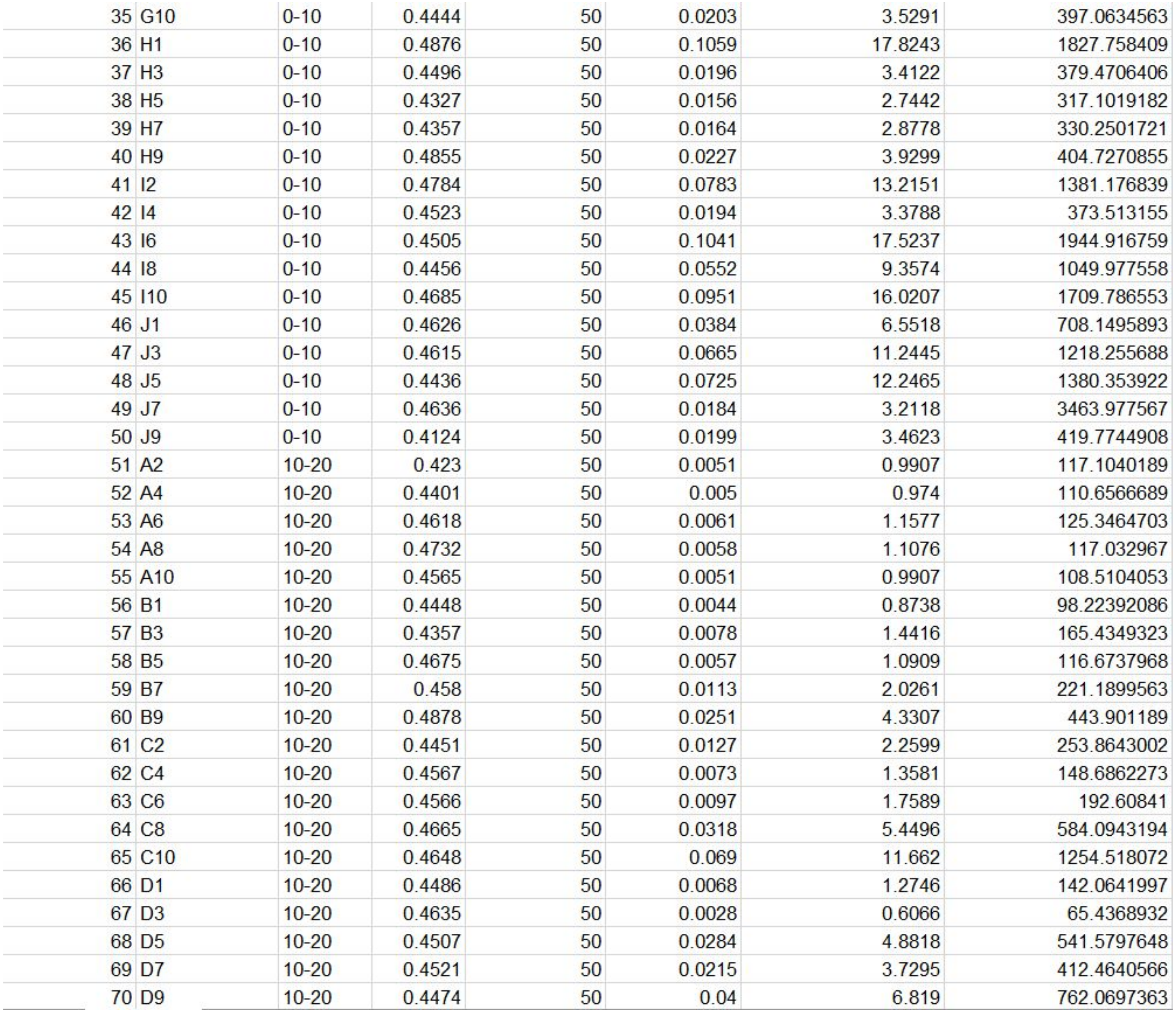
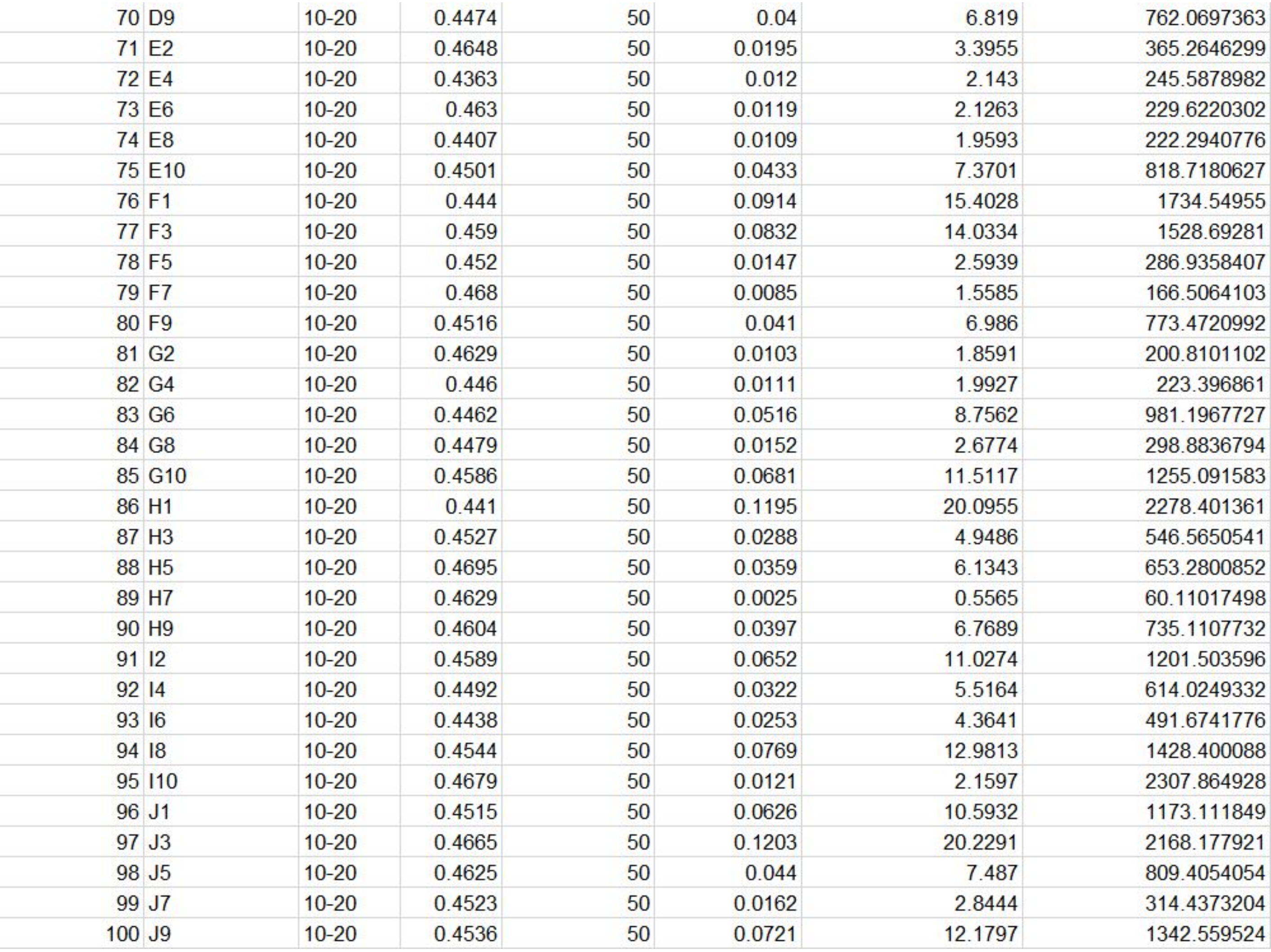
Appendix:



Sample	Grid	Depth	Mass (g)	Volume (ml)	Absorbance	Concentration (ppm)	Corrected Conc (ppm)
1	A2	0-10	0.4508	50	0.0033	0.6901	76.54170364
2	A4	0-10	0.4419	50	0.0023	0.5231	59.187599
3	A6	0-10	0.4461	50	0.0049	0.9573	107.2965703
4	A8	0-10	0.4592	50	0.0038	0.7736	84.23344948
5	A10	0-10	0.4657	50	0.003	0.64	68.71376423
6	B1	0-10	0.452	50	0.0108	1.9426	214.8893805
7	B3	0-10	0.4539	50	0.0015	0.3895	42.90592642
8	B5	0-10	0.4604	50	0.0004	0.2058	22.35013032
9	B7	0-10	0.4671	50	0.011	1.976	211.5178763
10	B9	0-10	0.4632	50	0.0312	5.3494	577.4395509
11	C2	0-10	0.4632	50	0.0084	1.5418	166.4291883
12	C4	0-10	0.4442	50	0.0061	1.1577	130.3129221
13	C6	0-10	0.4455	50	0.0175	3.0615	343.6026936
14	C8	0-10	0.4617	50	0.029	4.982	539.5278319
15	C10	0-10	0.41	50	0.078	13.165	1605.487805
16	D1	0-10	0.42	50	0.0135	2.3935	284.9404762
17	D3	0-10	0.49	50	0.0063	1.1911	121.5408163
18	D5	0-10	0.44	50	0.0235	4.0635	461.7613636
19	D7	0-10	0.47	50	0.0256	4.4142	469.5957447
20	D9	0-10	0.4459	50	0.0175	3.0615	343.2944606
21	E2	0-10	0.47	50	0.0234	4.0468	430.5106383
22	E4	0-10	0.42	50	0.0142	2.5104	298.8571429
23	E6	0-10	0.43	50	0.0096	1.7422	202.5813953
24	E8	0-10	0.42	50	0.0068	1.2746	151.7380952
25	E10	0-10	0.46	50	0.0328	5.6166	610.5
26	F1	0-10	0.43	50	0.0671	11.3447	1319.151163
27	F3	0-10	0.45	50	0.0333	5.7001	633.3444444
28	F5	0-10	0.46	50	0.0159	2.7943	303.7282609
29	F7	0-10	0.4234	50	0.0065	1.2245	144.6032121
30	F9	0-10	0.4044	50	0.0149	2.6273	324.8392681
31	G2	0-10	0.4926	50	0.0468	7.9546	807.409663
32	G4	0-10	0.453	50	0.0061	1.1577	127.781457
33	G6	0-10	0.4583	50	0.0142	2.5104	2738.817369
34	G8	0-10	0.4649	50	0.0086	1.5752	169.4127769



35	G10	0-10	0.4444	50	0.0203	3.5291	397.0634563
36	H1	0-10	0.4876	50	0.1059	17.8243	1827.758409
37	H3	0-10	0.4496	50	0.0196	3.4122	379.4706406
38	H5	0-10	0.4327	50	0.0156	2.7442	317.1019182
39	H7	0-10	0.4357	50	0.0164	2.8778	330.2501721
40	H9	0-10	0.4855	50	0.0227	3.9299	404.7270855
41	I2	0-10	0.4784	50	0.0783	13.2151	1381.176839
42	I4	0-10	0.4523	50	0.0194	3.3788	373.513155
43	I6	0-10	0.4505	50	0.1041	17.5237	1944.916759
44	I8	0-10	0.4456	50	0.0552	9.3574	1049.977558
45	I10	0-10	0.4685	50	0.0951	16.0207	1709.786553
46	J1	0-10	0.4626	50	0.0384	6.5518	708.1495893
47	J3	0-10	0.4615	50	0.0665	11.2445	1218.255688
48	J5	0-10	0.4436	50	0.0725	12.2465	1380.353922
49	J7	0-10	0.4636	50	0.0184	3.2118	3463.977567
50	J9	0-10	0.4124	50	0.0199	3.4623	419.7744908
51	A2	10-20	0.423	50	0.0051	0.9907	117.1040189
52	A4	10-20	0.4401	50	0.005	0.974	110.6566689
53	A6	10-20	0.4618	50	0.0061	1.1577	125.3464703
54	A8	10-20	0.4732	50	0.0058	1.1076	117.032967
55	A10	10-20	0.4565	50	0.0051	0.9907	108.5104053
56	B1	10-20	0.4448	50	0.0044	0.8738	98.22392086
57	B3	10-20	0.4357	50	0.0078	1.4416	165.4349323
58	B5	10-20	0.4675	50	0.0057	1.0909	116.6737968
59	B7	10-20	0.458	50	0.0113	2.0261	221.1899563
60	B9	10-20	0.4878	50	0.0251	4.3307	443.901189
61	C2	10-20	0.4451	50	0.0127	2.2599	253.8643002
62	C4	10-20	0.4567	50	0.0073	1.3581	148.6862273
63	C6	10-20	0.4566	50	0.0097	1.7589	192.60841
64	C8	10-20	0.4665	50	0.0318	5.4496	584.0943194
65	C10	10-20	0.4648	50	0.069	11.662	1254.518072
66	D1	10-20	0.4486	50	0.0068	1.2746	142.0641997
67	D3	10-20	0.4635	50	0.0028	0.6066	65.4368932
68	D5	10-20	0.4507	50	0.0284	4.8818	541.5797648
69	D7	10-20	0.4521	50	0.0215	3.7295	412.4640566
70	D9	10-20	0.4474	50	0.04	6.819	762.0697363



70	D9	10-20	0.4474	50	0.04	6.819	762.0697363
71	E2	10-20	0.4648	50	0.0195	3.3955	365.2646299
72	E4	10-20	0.4363	50	0.012	2.143	245.5878982
73	E6	10-20	0.463	50	0.0119	2.1263	229.6220302
74	E8	10-20	0.4407	50	0.0109	1.9593	222.2940776
75	E10	10-20	0.4501	50	0.0433	7.3701	818.7180627
76	F1	10-20	0.444	50	0.0914	15.4028	1734.54955
77	F3	10-20	0.459	50	0.0832	14.0334	1528.69281
78	F5	10-20	0.452	50	0.0147	2.5939	286.9358407
79	F7	10-20	0.468	50	0.0085	1.5585	166.5064103
80	F9	10-20	0.4516	50	0.041	6.986	773.4720992
81	G2	10-20	0.4629	50	0.0103	1.8591	200.8101102
82	G4	10-20	0.446	50	0.0111	1.9927	223.396861
83	G6	10-20	0.4462	50	0.0516	8.7562	981.1967727
84	G8	10-20	0.4479	50	0.0152	2.6774	298.8836794
85	G10	10-20	0.4586	50	0.0681	11.5117	1255.091583
86	H1	10-20	0.441	50	0.1195	20.0955	2278.401361
87	H3	10-20	0.4527	50	0.0288	4.9486	546.5650541
88	H5	10-20	0.4695	50	0.0359	6.1343	653.2800852
89	H7	10-20	0.4629	50	0.0025	0.5565	60.11017498
90	H9	10-20	0.4604	50	0.0397	6.7689	735.1107732
91	I2	10-20	0.4589	50	0.0652	11.0274	1201.503596
92	I4	10-20	0.4492	50	0.0322	5.5164	614.0249332
93	I6	10-20	0.4438	50	0.0253	4.3641	491.6741776
94	I8	10-20	0.4544	50	0.0769	12.9813	1428.400088
95	I10	10-20	0.4679	50	0.0121	2.1597	2307.864928
96	J1	10-20	0.4515	50	0.0626	10.5932	1173.111849
97	J3	10-20	0.4665	50	0.1203	20.2291	2168.177921
98	J5	10-20	0.4625	50	0.044	7.487	809.4054054
99	J7	10-20	0.4523	50	0.0162	2.8444	314.4373204
100	J9	10-20	0.4536	50	0.0721	12.1797	1342.559524