Legacy Pb contamination in the soils of three Durham city parks:

Do secondary forest organic horizons effectively blanket Pb in city park soils contaminated by historic waste incineration?

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I. Executive Summary

Lead (Pb) has historically been used in many products such as gasoline, paint, batteries, ceramics, pipes and plumbing, solders, and cosmetics, and Pb contamination from these materials and their waste streams is widespread around the world. Pb is a highly insoluble and persistent contaminant that accumulates in the environment, especially in urban soils; to this day, soil Pb concentrations remain high in many cities, posing a significant long-term public health and environmental risk. Some remediation options are available for Pb, with the most effective being removal and replacement of the contaminated soil. However, plants that can tolerate soil Pb may be effective at phytostabilization. In phytostabilization, soil Pb is immobilized both physically and chemically by the roots, while also being sequestered by new layers of organic matter and soil that accumulate on the surface.

Throughout the early 1900s, the city of Durham, NC operated neighborhood municipal incinerators which combusted most of the city's waste, including waste collected from homes, businesses, and public street cleaning. Around 1950, the four of the incinerator sites were closed and converted into public parks, with playgrounds, grass fields, picnic benches, sports facilities, and walking paths. These are now Walltown, East End, East Durham, and Lyon Parks. The parks currently contain streams and large areas of secondary forest cover, which have been largely unmanaged throughout the last century. From local newspaper articles, we have direct evidence for the disposal of incinerator refuse at these sites and other Durham parks. While historic news accounts describe the incinerator sites being covered with topsoil, until this study there has been no monitoring of the status of contaminant metals in the soils throughout the parks. We hypothesized that the surface soils of these parks had elevated Pb concentrations as the result of the parks' history of incineration.

Our primary objectives were to:

1. Measure total mineral surface soil Pb concentrations across three of Durham's urban parks which were historically used for waste incineration (Walltown, East End, and East Durham Parks).

2. Assess whether secondary hardwood forests have accumulated organic horizons that were effective barriers to Pb-contaminated mineral soil below.

We sampled mineral surface soil and organic horizon according to a stratified random sampling design, and the samples were measured for total Pb with an Olympus Vanta pXRF instrument. Data were analyzed using R and ArcGIS Pro, resulting in statistical models and spatial interpolations.

Our main results were:

1. Mineral soil Pb concentrations across Walltown, East End, and East Durham Parks are elevated above both geologic background levels and several EPA hazard thresholds, especially in some highly-trafficked areas.
2. Hardwood forest organic horizons provide a blanket for highly Pb-contaminated mineral soil, but a significant amounts of surface soil Pb is mixed up into these O horizons. Thus, exposure risk is not eliminated and can remain quite high.

Our results show that all three parks have total Pb in surface soils (0-2.5 cm) well above the geologic background (0-30 ppm), with many soils exceeding the US EPA's hazard thresholds for gardening (100 ppm), residential play areas (400 ppm), and residential non-play areas (1200 ppm). For all three parks combined, mineral soil Pb ranged from 8 to 2342 ppm, with a mean of 201 ppm and a median of 93 ppm. A notable hotspot with extremely high Pb was mapped throughout the southeastern portion of East Durham Park north of East Main St., spanning a grassy field and part a secondary forest (Figure 12). Mineral soil Pb in this hotspot ranged from 694 to 2342 ppm. This is of particular concern because this field is adjacent to an apartment building, and residents appear to use this area to play, garden, and park their cars.

Additionally, our study demonstrates that while hardwood O horizons provide a physical barrier to exposure for highly contaminated mineral soil, a significant amount of mineral soil Pb is mixed up into the O horizons. This relationship differed significantly between the upper O1/O2 and the lower O3 horizons. Pb concentration in the lower O3 horizon increased by 0.6 ppm for every 1 ppm increase in Pb increase in the mineral soil, with an adjusted R^2 of 0.86.

This means that the lower O3 horizon has about 60% of the Pb concentration of the mineral soil below. In contrast, Pb concentration in the upper O1/O2 horizon increased by 0.1 ppm for every 1 ppm increase in Pb increase in the mineral soil, with an adjusted R^2 of 0.49. This means that the upper O1/O2 horizons have about 10% of the Pb concentration of the mineral soil below,

Our results suggest limitations to phytostabilization as tool to reduce Pb exposure, particularly in hardwood forests where there is relatively rapid decomposition and bioturbation in the O horizons compared to many coniferous forests. Overall, the spatial distribution of soil Pb concentrations demonstrates the complicated land use history of these landscapes, pointing towards multiple sources of Pb inputs and outputs throughout the 20th century.

Based on articles in historic newspapers from five cities across the USA, many municipalities may have public parks converted from historic waste incinerator sites; these sites may be contaminated with Pb and other metals that would have accumulated in ash and cinders, posing an exposure risk to residents who visit the parks.

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III. Abstract

As a result of its historical uses in common materials, lead (Pb) tends to accumulate in urban soils throughout the world. Durham, NC operated at least four waste incinerators in the first half of the 20th century, and around 1950, these sites were converted into public parks containing large areas of secondary urban forest. Our objective was to measure total mineral surface soil Pb in three of these parks and to assess whether secondary hardwood organic horizons (O horizons) effectively blanket Pb-contaminated soil below. Our results show that all the parks have total Pb in surface soils (0-2.5 cm) well above the geologic background (0-30 ppm), with many soils exceeding the US EPA's hazard thresholds for gardening (100 ppm), residential play areas (400 ppm), and residential non-play areas (1200 ppm). Additionally, our study demonstrates that while hardwood O horizons provide a physical barrier to exposure for highly contaminated mineral soil, a significant amount of mineral soil Pb is mixed up into the O horizons. The upper O1 and O2 horizons have about 10% of the Pb concentration of the mineral soil below, and the lower O3 horizon has about 60% of the Pb concentration of the mineral soil below. This highlights the limitations of phytostabilization as tool to reduce Pb exposure, particularly in hardwood forests where there is rapid decomposition and bioturbation in the O horizons. Based on historic newspapers from cities across the USA, we suggest that many municipalities have public parks with contaminant metals from historic waste incineration, posing a similar exposure threat to residents.

IV. Introduction

Soil Pb and Phytostabilization:

Lead (Pb) has historically been used in many products such as gasoline, paint, batteries, ceramics, pipes and plumbing, solders, and cosmetics, and residual Pb contamination from these materials is widespread around the world [1–3]. Even at low levels of exposure, Pb can cause dire health issues for both children and adults, ranging from cardiovascular stress to neurological damage [4–8]. Cognitive and behavioral impairments in children have been thoroughly demonstrated by large environmental health data sets [4–8].

It is a highly persistent and insoluble contaminant in the environment, and to this day, soil concentrations remain high in many cities, posing a significant long-term public health and environmental risk [2,6,9,10]. Soil Pb an is garnering increased attention in the environmental and public health fields, being studied globally as a pathway to exposure [9]. Many studies demonstrate Pb exposure through soil, through activities such as gardening, building, playing, and tracking dust into home [11–14]. Children are especially vulnerable to this kind of exposure sue to their behaviors, especially through ingestion and inhalation, and there is a direct relationship between soil Pb and blood Pb levels in children [1,11,13–16].

The health risks associated with Pb exposure pose a serious environmental justice problem, since marginalized and socioeconomically disadvantaged communities tend to have higher Pb exposures than the rest of the population [3,7,17]. This trend is also evident in soil Pb exposure, since many black and other minority communities have been systemically driven to live and work in and around structures that serve as Pb sources (such as older houses, gas stations, factories, and waste incinerators and landfills) [3,7,17,18].

Pb is present naturally at low levels in many soils found around the world, due to the underlying rock that the soil is created from. These geologic background levels range from 10-30 ppm, on average [19–21]. The US EPA has set several concentration thresholds for soil Pb to limit human exposure (Table 1). In 1994, it set soil screening levels (SSLs) which state that a soil Pb hazard is present when soil from a residential play area surpasses 400 ppm Pb, and when soil from a residential non-play area surpasses 1,200 ppm Pb [22]. Then, in 2014, it published a technical review that recommended keeping soil under 100 ppm Pb for safe gardening activities [23].

Table 1: Hazardous soil Pb thresholds set by the US EPA [22,23].

Concentration	**Threshold**	**Source**
<30 ppm	Background geologic levels	See above
<100 ppm	Safe for gardening activities	EPA, 2014
<400 ppm	Safe for residential play areas	EPA, 1994
<1200 ppm	Safe for residential non-play areas	EPA, 1994

Some remediation options are available for Pb, with the most effective being removal and replacement of the contaminated soil, or stabilizing and burying the soil [2,10]. Some other methods are also used, such as chemical stabilization/solidification for sequestration or chemical mobilization for extraction by soil washing [24–26]. Much literature exists on the possibilities of phytoextraction of soil Pb, with some studies suggesting that plants can relocate Pb from the soil into their tissues, particularly in the presence of soil amendments such as chelates, lime, and cement [25,27]. However, most plants have physiological mechanisms that exclude Pb from their tissues, and even if they do take up Pb, it usually stays in the roots and is not transferred to stems and foliage – which is actually considered phytostabilization [10,25,27–29]. One recent meta-analysis found that no plants actually meet hyperaccumulator criteria without amendments, meaning that plants are largely unable to extract Pb in the quantities and time frames necessary for remediation projects [10,27]. Several studies and review papers also underpin the ineffectiveness of Pb phytoextraction as a remediation tool, despite the fact that plants can effectively accumulate some other heavy metals in their aerial tissues, such as cadmium, nickel, and zinc [10,27,30–32,32].

However, plants that can tolerate soil Pb may be effective at phytostabilization [10,27,31]. In phytostabilization, soil Pb is immobilized both physically and chemically by the roots, while also being sequestered by new layers of organic matter and soil that accumulate on the surface [3,10,24,31,33,34]. This reduces exposure from direct contact, soil erosion/migration, air turbation (inhalation of contaminated particulates), or water leaching (ingestion of contaminated water) [10,33]. Many studies have enhanced phytostabilization with various amendments such as compost, manure, biochar, acids, phosphorus, mycorrhizal fungi, and chelates, which help by stimulating plant growth, improving plant Pb tolerance, increasing root Pb uptake, decreasing Pb bioavailability, and improving soil structure (by creating water stable aggregates and irregular porosity) [25,32,34–39]. It is important to note, however, that phytostabilization is only effective in the root zone of plants [24].

Durham's Waste Incinerators:

Throughout the early 1900s, the city of Durham, NC operated four municipal incinerators which processed most of the city's waste, including waste collected from homes, businesses, and public street cleaning (Figures 1-4) [40–45]. Each incinerator had a capacity of processing 15-20 tons of waste [43]. They went out of commission around 1940, when the city constructed a new centralized incinerator in northeast Durham [40,41,44,46–48]. Some incinerators were demolished soon after, while others were left abandoned for longer periods of time, such as the facility located at what is now East Durham Park [49–52]. There is evidence of lively public debate over the fate of both the old and new incinerators, with many Durham residents reporting, petitioning, and suing over concerns that they are significant nuisances in their neighborhoods [44–47,53,54].

Around 1950, all four of the unused incinerator sites were converted into public parks, with playgrounds, grass fields, picnic benches, sports facilities, and walking paths [49,51,55]. These are now Walltown, East End, East Durham, and Lyon Parks. There is evidence that potentially high Pb materials were used as fill in some of these parks during the landscaping process. For example, fill for some of the playgrounds came from dirt and rubble from streets that were being renovated [49]. Additionally, "500 truckloads" of ash and cinders from refuse piles at the Walltown Park incinerator were used as fill covered by topsoil at another Durham park [55]. However, "2000 truckloads" of cinders and ash were removed from the Walltown site in total, which could have been used as fill at other similar sites [55].

All four parks currently contain streams and large areas of secondary forest cover, which appear to have been unmanaged throughout the last century. Walltown Park has 1.06 ha of forest cover (42% of its total area), East End Park has 1.38 ha of forest cover (44% of its total area), and East Durham Park has 1.10 ha of forest cover (75% of its total area). They are dominated by native hardwood trees and invasive plants, with some native pines present in East Durham and East End Parks. The forest canopies range from being fairly open to entirely closed, depending on the soil characteristics. Based on airplane and satellite imagery from the 1900s, it seems that most of these incinerator sites were barren or covered in low-lying shrubs in the early 20th century, and much of this land has been left to undergo natural succession, which has produced the secondary forests present today (Figure 5). Most of the incinerator buildings can be easily identified in 1940 aerial photography, along with the roads and refuse piles associated with them (Figure 4).

We hypothesized that these parks would have high levels of soil Pb contamination, since the waste processed at these incinerators included many common household products that contained Pb, including batteries, ceramics, pipes, solders, and cosmetics, as well as housepaint and gasoline exhaust that accumulated on the streets. Many studies from around the world have concluded that waste incineration is a source of heavy metal contamination in surrounding soils [18,56–60]. We also anticipated the contamination levels and patterns to be different among the sites, considering their different land use histories. Additionally, the presence of nearly 70-year-old secondary hardwood forests with well-developed organic horizons (O horizons) allowed us to study the effectiveness of organic matter as a stabilization and exposure mitigation tool. This part of the study relied on the knowledge that this organic matter from canopy litterfall did not contain appreciable Pb, since plants are unable to accumulate Pb in their stems, branches, and foliage, and that there have been no recent anthropogenic Pb inputs, since these forests appear unmanaged since the 1950's.

Project Objectives:

Our primary objectives were to:

3. Measure total mineral soil Pb concentrations across three of Durham's urban parks which used to be waste incinerator sites.
4. Assess whether secondary hardwood organic horizons provide an effective barrier to Pb-contaminated mineral soil below.

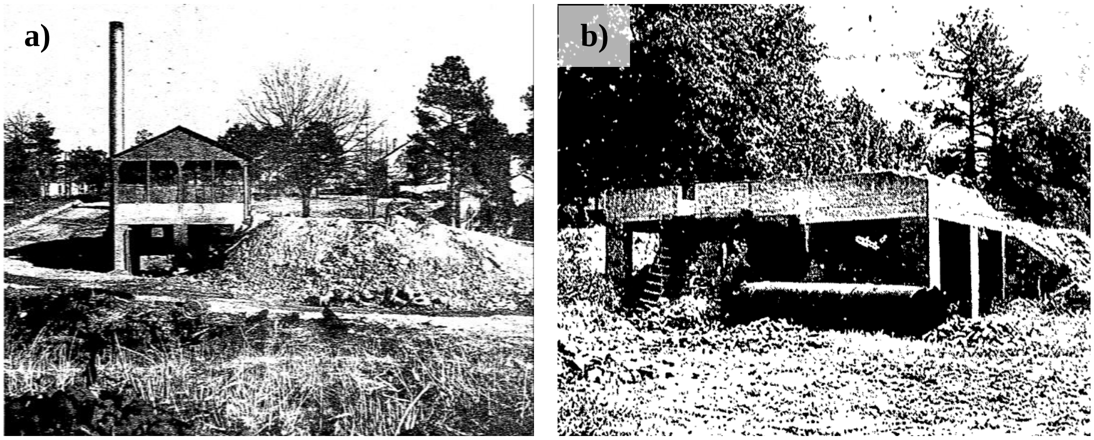

*Figure 1: Newspaper photographs of Durham's historical waste incinerators; **a)** A photograph of one of the four incinerators, published in the Durham Morning Herald in 1940* [44]*; **b)** A photograph of the partially-demolished Walltown incinerator, published in the Durham Morning Herald in 1950* [51].

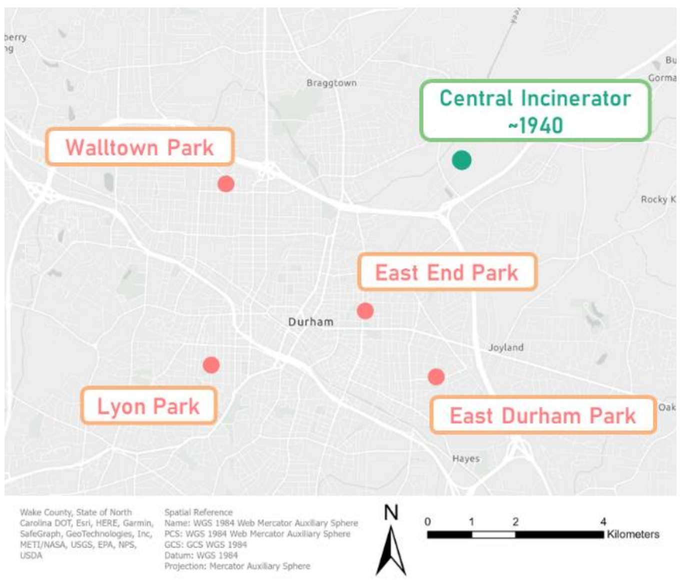

Figure 2: The locations of the four original waste incinerators and the new centralized waste incinerator built around 1940, shown on a current map of Durham, NC.

Figure 3: A 1937 Map of Durham, published by the Durham Department of Public Works, with the four original waste incinerator sites labelled along with their waste-processing capacity [43].

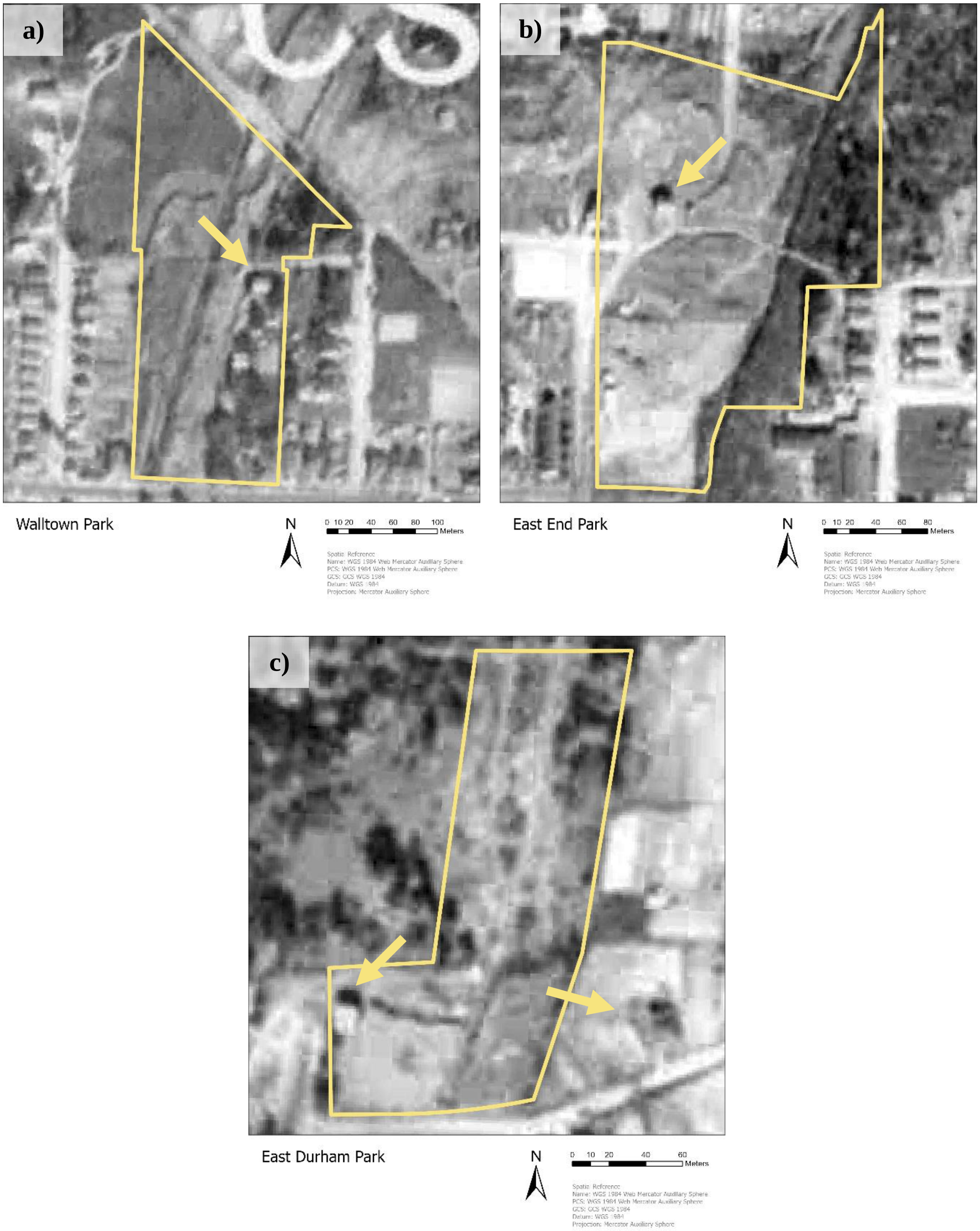

Figure 4: 1940 aerial imagery of three of the parks which used to be waste incinerator sites, with lines showing the current extent of the parks and arrows indicating the possible locations of the incinerator buildings; ***a)*** *Walltown Park;* ***b)*** *East End Park;* ***c)*** *East Durham Park* [61].

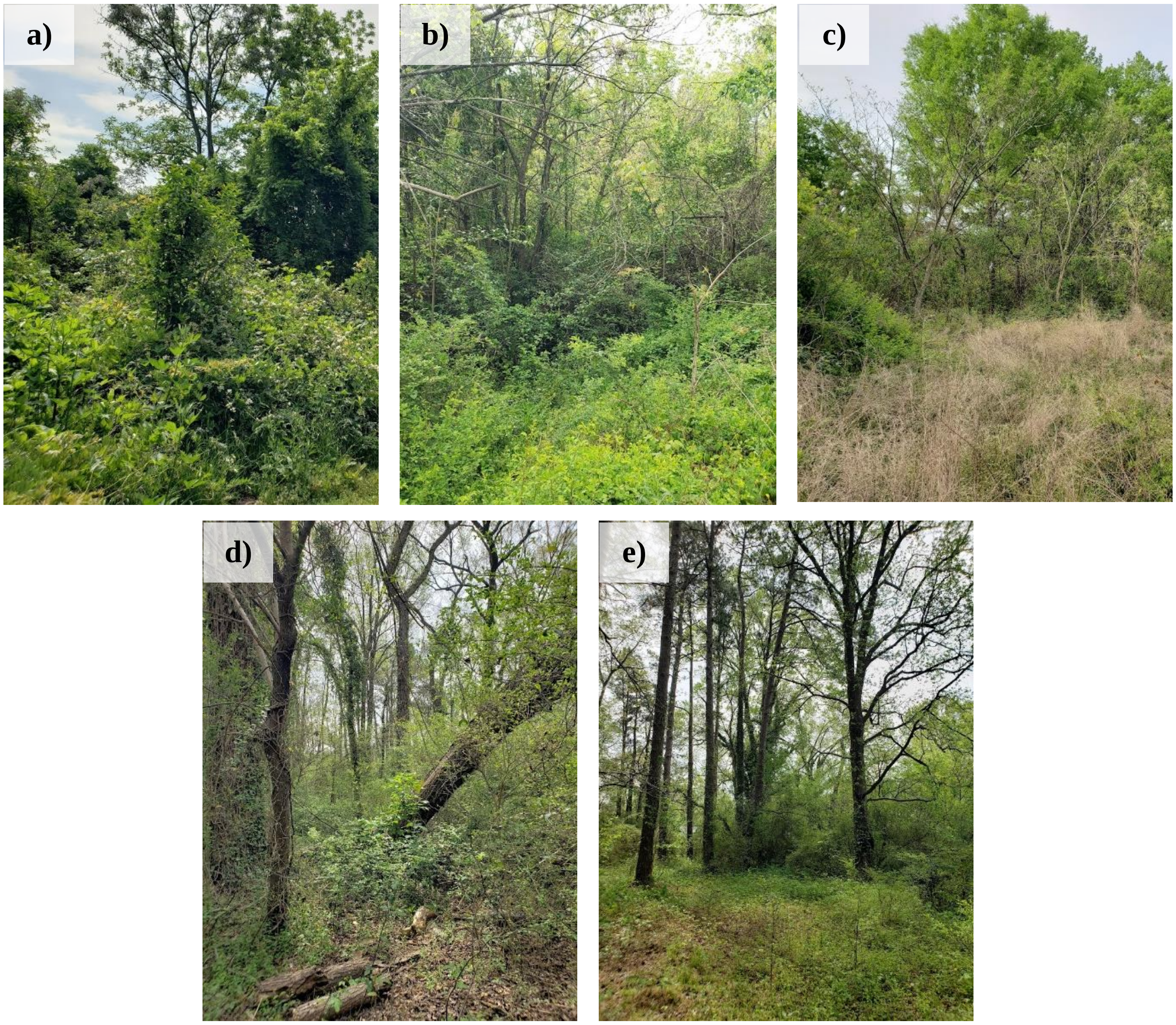

Figure 5: Photographs of the current forest cover in the three of the parks which used to be waste incinerator sites; ***a)*** *Walltown Park;* ***b)*** *East End Park;* ***c)*** *East End Park;* ***d)*** *East Durham Park;* ***e)*** *East Durham Park.*

V. Methods

Background Research:

We conducted preliminary research on the location and history of the incinerator sites at Walltown, East End, and East Durham Parks in order to create an appropriate sample design. Lyon Park was left out of our study due to time constraints and the fact that the old incinerator location is not a heavily-trafficked part of the park. The incinerator sites that would become city parks are explicitly labelled on a 1937 street map of Durham (Figure 3), and I georectified this map along with 1940, 1955, and 1972 North Carolina aerial imagery (Figure 4) [43,61]. Overlaying these maps and photos, I found the geographic locations of the incinerators on their respective city blocks. Buildings are easy to identify this way, even in low-resolution imagery, since they have distinct shapes, colors, and shadows. However, these locations are only best estimates, since the 1937 map could only be used to identify the city blocks on which the incinerators were located, and the precise locations were based on information pieced together from the imagery and local newspaper articles. At East Durham Park, I identified multiple buildings which could have been the waste incinerator site, piecing together information from newspaper articles, aerial imagery, and Pb contamination patterns. We used these layers both to qualitatively inform our understanding of land cover/land use at the time and to create point features for the incinerators.

After initial visits to each park to collect preliminary soil samples and qualify the land cover, I divided each park into different sampling strata based on current land cover and inferred land use history (Figure 6). I used ArcGIS Online to acquire shapefiles for Durham's parks and ArcGIS Pro to subdivide them into the sampling strata. For these delineations, I used aerial imagery from 1940, 1955, and 1972, and Google Earth satellite imagery from different seasons that date back to the 1980's [61]. I removed buildings and paved surfaces from the sampleable areas. I used ArcGIS Pro to generate random sample points about 15 meters apart in each stratum, with a final sampling density of about 1 point per 250 m^2. This resulted in a total number of 269 sample points across all three parks. This stratified random sampling was chosen in order to help ensure coverage of all land cover types within the parks while also avoiding any regularly-spaced vegetative, edaphic, geologic, or topographic patterns that might coincide with our sample point density.

Field Sampling:

Throughout September 2021 to May 2021, we conducted mineral surface soil sampling at these sample points in Walltown, East End, and East Durham Parks. At each sample point, we composited four samples from the upper 2.5 cm of mineral soil (A horizon) from a 30x30 cm area, excluding O horizons [3].

In October 2022, we conducted O horizon sampling at East Durham Park, across a gradient of mineral soil Pb concentrations under secondary forests. This park was selected because it had the widest range of mineral soil Pb under a consistent and well-developed O horizon, ranging from 28 to 2266 ppm. This allowed us to test whether mineral soil Pb is bioturbated up into the O horizon. We collected the upper and lower O horizon layers from an area with a 30 cm diameter at each point, along with a sample of the mineral soil directly below. We classified the upper O horizon as O1/O2, which included fresh litter and debris, with individual components such as leaves, twigs, and bark mostly intact and easily recognizable. We classified the lower O horizon as O3, which included organic matter was well decomposed into unrecognizable, amorphous humus that had begun to mix with the mineral soil below. Our O1, O2, and O3 classes correspond directly to Oi, Oe, and Oa designations often used by others.

Lab Analysis:

In the lab, the mineral soil samples were air dried, homogenized and passed through a 2 mm sieve. The O horizon samples were air dried, homogenized, subsampled, and ground with a Wiley Mill using a 0.4 mm screen. These homogenized samples were then measured for total Pb with an Olympus Vanta pXRF instrument that was calibrated for measuring total Pb between 5 and 50,000 mg/kg (ppm) [3].

Data Analysis:

I used R to clean and compile the chemical and spatial data into a single data set that could be used for statistical and geospatial analysis. For the statistical models, I calculated several relevant environmental variables for each sample point in ArcGIS Pro. I calculated each point's elevation, slope, and topographic position index from an NC digital elevation model, and I calculated each point's distance to the incinerators and nearby roads [62]. Thus, I created one master data set with the location, Pb concentration, and environmental variables for each soil sample.

Using ArcGIS Pro, I interpolated the sample point Pb concentrations in order to create a full Pb map for each park. I tested multiple interpolation methods, including simpler ones like natural neighbor, inverse distance weighted, and spline, as well as more complex ones such as kriging. I decided to use the maps produced by the inverse distance weighted interpolation, as it seemed like the most straightforward and parsimonious way to estimate Pb levels between sample points (Figures 10-12). I used a variable search radius of 10 points and a power of 2 for the exponent of distance. This method allowed interpolation of the entire park areas, not just the extent of the sample points, as is the case with natural neighbor. It also retained some of the true spatial heterogeneity in Pb levels that was smoothed over by kriging. The land use history of these parks is clearly complex – many gradual processes and sporadic events have interacted to create contemporary soil Pb distributions. Thus, it was difficult to find equations that accurately model the underlying spatial autocorrelation of sample points, and the kriging process created maps with strikingly low variation in Pb levels.

I created many generalized linear models in R to relate environmental variables to mineral soil Pb concentrations across the three parks. Due to the strong skew of the data, they were log-transformed to fulfill the assumption of normality. However, after trying many combinations of explanatory variables and random effects, I decided to leave most of these statistical models out of my final results. The relationships between variables were mostly inconsistent between the parks, meaning that the significant explanatory variables also differed greatly between the parks. This is likely related to the complicated and diverse land use history of these incinerator sites, which is not fully captured by current environmental variables and probably explains some of the spatial variation in Pb concentration.

To model the relationship of O horizon Pb concentrations to mineral soil Pb concentrations, I generated simple linear regressions in R, which appeared to capture the relationships well. I regressed the O1/O2 and O3 horizon Pb with mineral soil Pb, and I regressed the O1/O2 horizon Pb with the O3 horizon Pb to explore the patterns occurring within the O horizon.

*Figure 6: Sampling strata used for mineral surface soil samples in three of the parks which used to be waste incinerator sites, with Google Earth imagery from May 2017; **a)** Walltown Park; **b)** East End Park; **c)** East Durham Park.*

VI. Results

Soil Pb:

Mineral surface soil (0-2.5 cm) Pb levels in all parks reached levels well above geologic background levels of 0-30 ppm [19–21]. In all three parks, the historic incinerators were apparently located in what are now highly-trafficked areas such as grass fields, sports facilities, playgrounds, and picnic areas. The parks also had alarmingly high Pb levels in some such areas. For all three parks combined, mineral soil Pb ranged from 8 to 2342 ppm, with its distribution having a strong right skew, a mean of 201 ppm, and a median of 93 ppm (Figure 7).

When data from all three parks is aggregated and parks are accounted for as an explanatory variable, it appears that the current presence of forest cover may have a slightly negative effect on mineral soil Pb concentrations (Figure 9). In areas with forest cover, Pb concentration is predicted to be lower by a factor of 0.25 than areas without forest cover, at a significance level of $P = 0.074$. However, as mentioned in the methods, these patterns could be attributed to inconsistent Pb inputs and other human activities.

Walltown Park: Mineral soil Pb in Walltown park ranged from 13 to 1338 ppm, with its distribution having a strong right skew, a mean of 162 ppm, and a median of 105 ppm (Figure 8). Many samples were on the lower end of the range (but still well above geologic background levels), with several Pb hotspots spread out along the vegetated riparian zone running north-south through the middle of the park. Additionally, some of the grassy areas near the basketball courts and horseshoe pits had elevated Pb. In contrast, some areas where clean fill was used during landscaping and construction, such as baseball fields and the community center, had relatively low Pb (Figure 10).

East End Park: Mineral soil Pb in East End Park ranged from 8 to 1364 ppm, with its distribution having a strong right skew, a mean of 127 ppm, and a median of 57 ppm (Figure 8). Many samples were on the lower end of the range (but still well above geologic background levels), especially between the tennis courts and throughout the riparian zone in the forested area.

In the southern region of the park, behind a fence with a locked gate, Pb was very high in a number of soil samples. While this area was likely not affected by historic waste incineration, it was historically used by the city for paint and sign production. This is concerning because this area lacks much vegetative cover and contaminated surface soil particles can be easily eroded by wind and water into the neighboring environment. Just north of the paint and sign shop, there is an area of extremely low Pb, which is mostly covered by impermeable concrete and gravel; these surfaces may act as a barrier to the contaminated soil below and likely allow all new Pb inputs to be eroded into adjacent soil (Figure 11).

East Durham Park: Mineral soil Pb in East Durham Park ranged from 28 to 2342 ppm, with its distribution having a strong right skew, a mean of 405 ppm, and a median of 107 ppm (Figure 8). Many samples were on the lower end of the range (but still well above geologic background levels), especially throughout the northern forested area, with a smaller hotspot on the western grassy area just north of the playground. A notable hotspot with extremely high Pb was mapped throughout the southeastern region of the park, spanning a grassy field and part the forested areas (Figure 12). Mineral soil Pb in this hotspot ranged from 694 to 2342 ppm. This is of particular concern because this field is adjacent to an apartment building, and residents appear to use this area to play, garden, and park their cars. This hotspot indicates a large, direct input of Pb into the soil, possibly from a refuse pile, which supports the possibility that the incinerator may have actually been located near the southeastern boundary of the park and not near the current playground. This possibility is also underpinned by several newspaper articles from the 1950s, which detail that playground construction had begun by 1950, but that the incinerator building and its buried debris were still present somewhere on that site in 1952 (experiencing an underground fire in that year) [49,51,52].

O Horizon Pb:

Pb concentration in the O horizons in East Durham Park was positively correlated with the Pb concentration in the underlying mineral soil (A horizon) Pb (Figures 13-14). This relationship differed significantly between the upper O1/O2 horizon and the lower O3 horizon. Pb concentration in the lower O3 horizon increased by 0.6 ppm for every 1 ppm increase in Pb increase in the mineral soil, with an adjusted R^2 of 0.86. This means that 86% of the variability in O1/O2 horizon Pb can be explained by Pb in the mineral soil. In contrast, Pb concentration in the upper O1/O2 horizon increased by 0.1 ppm for every 1 ppm increase in Pb increase in the mineral soil, with an adjusted R^2 of 0.49. This means that 49% of the variability in O1/O2 horizon Pb can be explained by Pb in the mineral soil. When O1/O2 horizon Pb is regressed against O3 horizon Pb, O1/O2 horizon Pb increases by 0.1 ppm for every 1 ppm increase in in the O3 horizon Pb, with an adjusted R^2 of 0.35. These results demonstrate that much lower quantities of soil Pb are mixed up into the upper O horizon than the lower O horizon; the upper O horizon maintains at least an order of magnitude lower Pb levels than the mineral soil below it. The lower O horizon does have lower Pb levels than the mineral soil below it, but clearly a significant amount of soil Pb is mixed up into this layer.

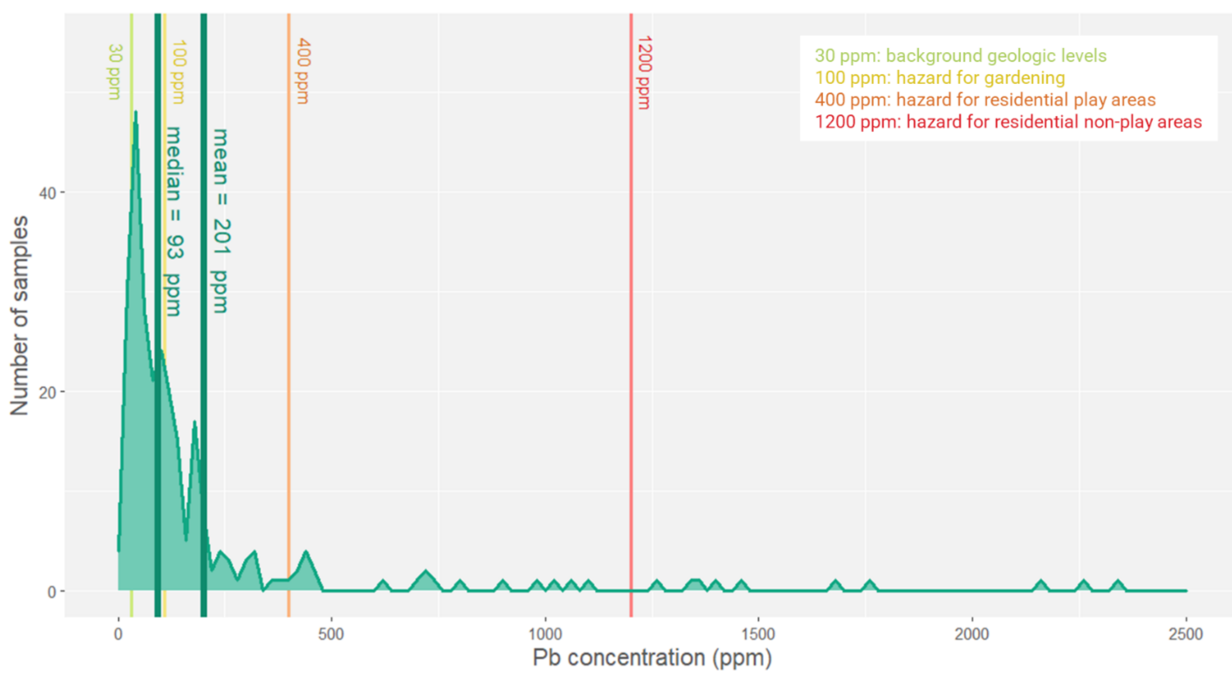

Figure 7: Distribution of Pb concentration in soil samples across all parks, with geologic background levels and US EPA hazard thresholds (Table 1).

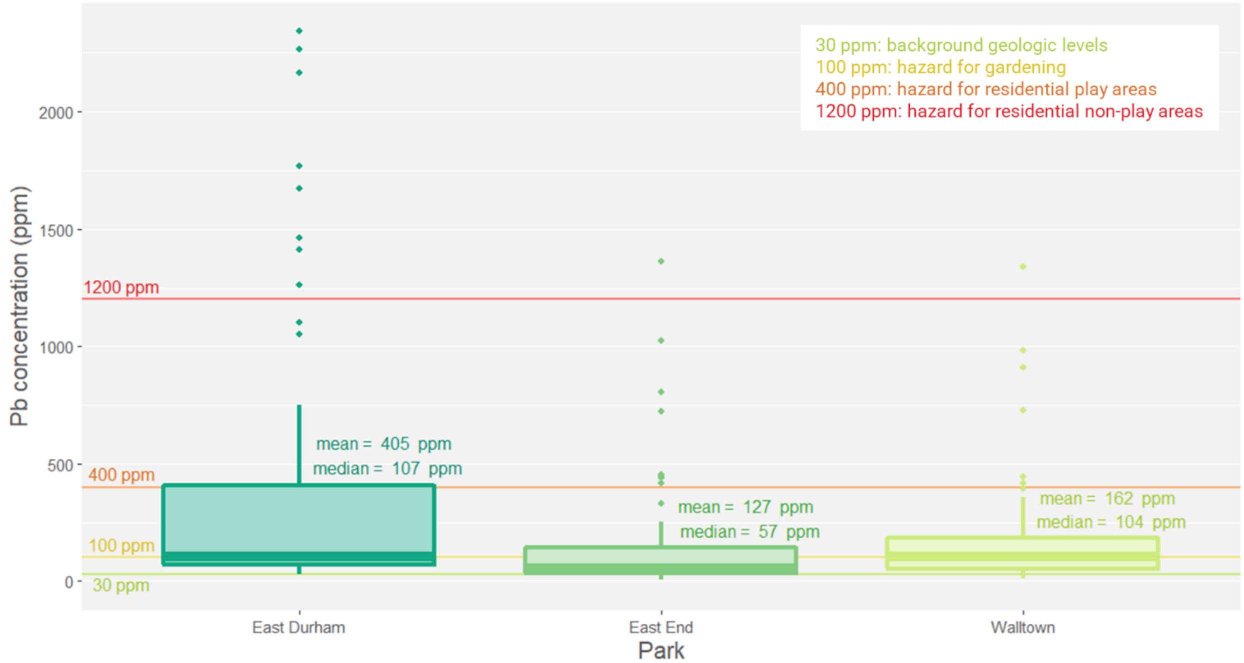

Figure 8: Distribution of Pb concentration in soil samples broken down per park, with geologic background levels and US EPA hazard thresholds (Table 1).

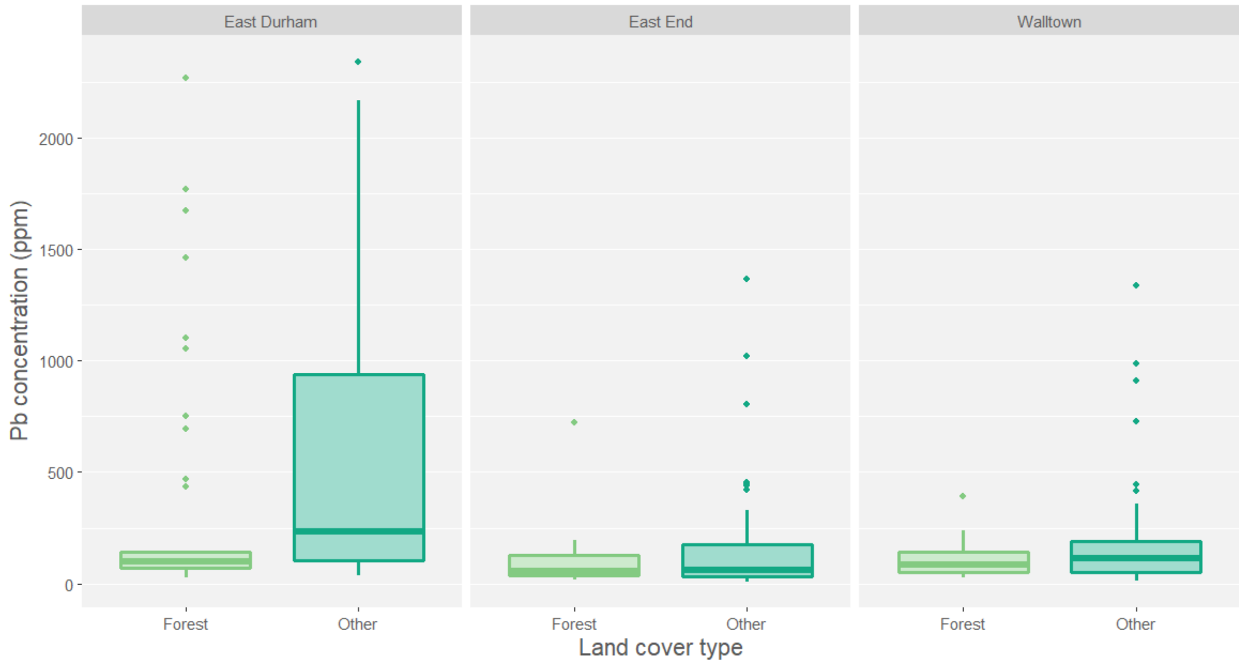

Figure 9: Distribution of Pb concentration in soil samples broken down per park and land cover type.

Figure 10: Map of interpolated mineral soil Pb concentrations in Walltown Park.

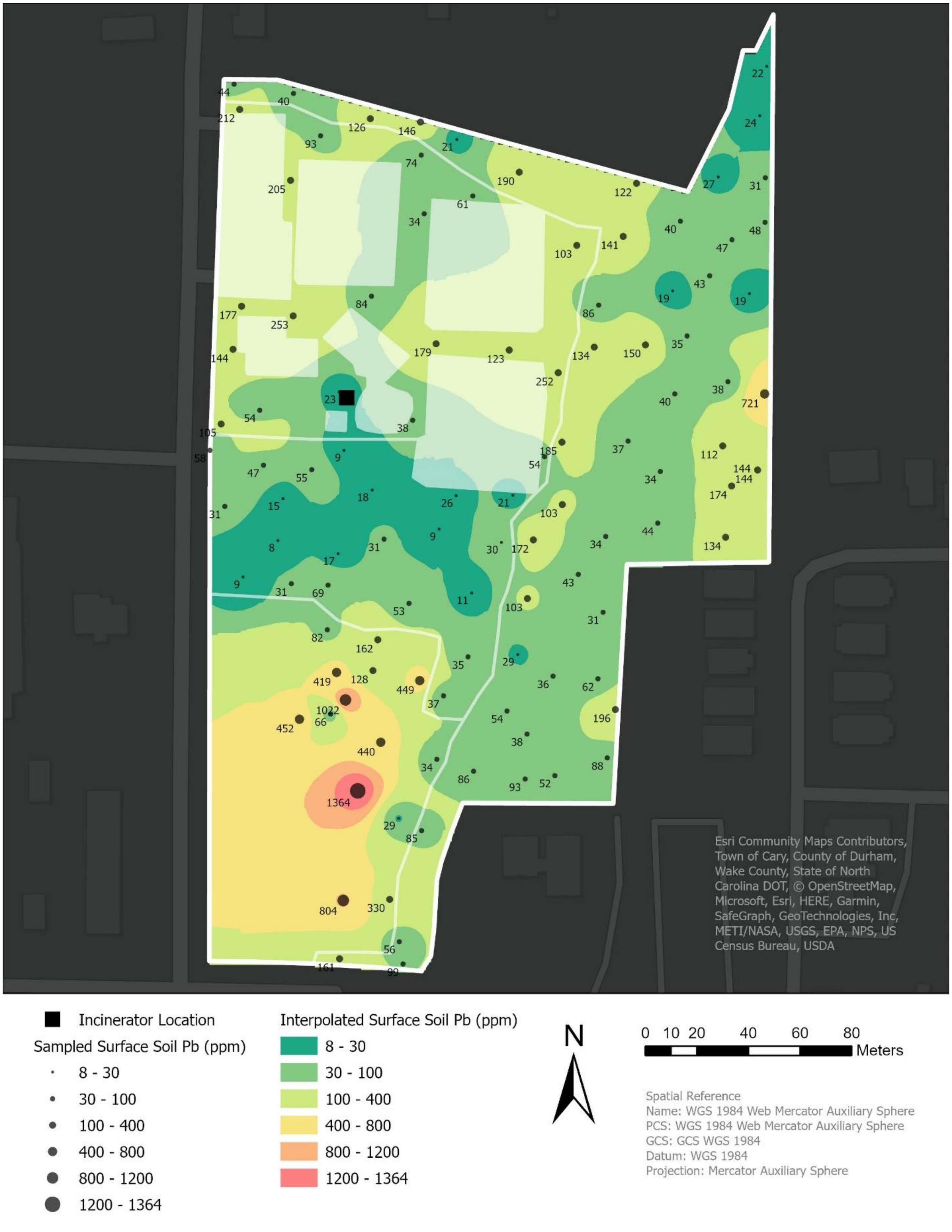

Figure 11: Map of interpolated mineral soil Pb concentrations in East End Park.

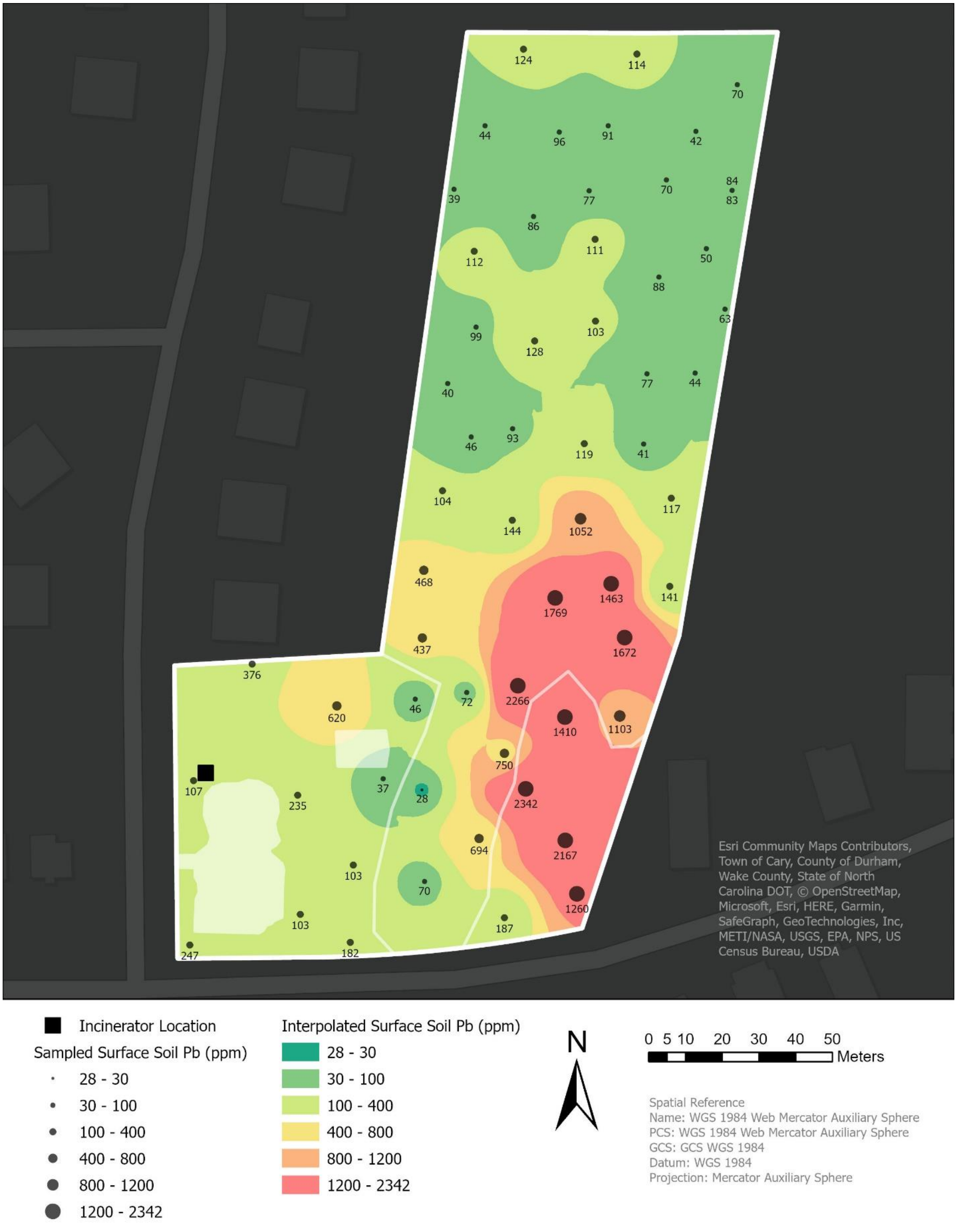

Figure 12: Map of interpolated mineral soil Pb concentrations in East Durham Park.

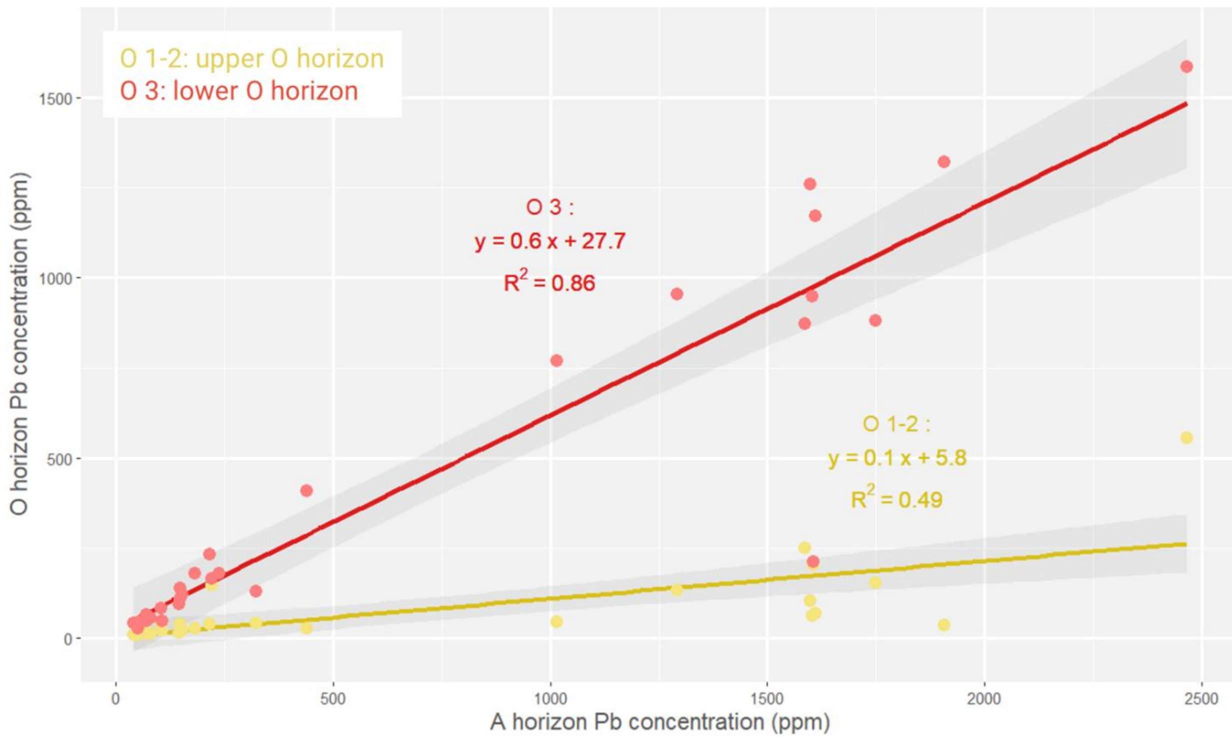

Figure 13: Graph of O horizon (organic matter) Pb concentrations vs. A horizon (mineral soil) Pb concentrations, with respective the linear regressions.

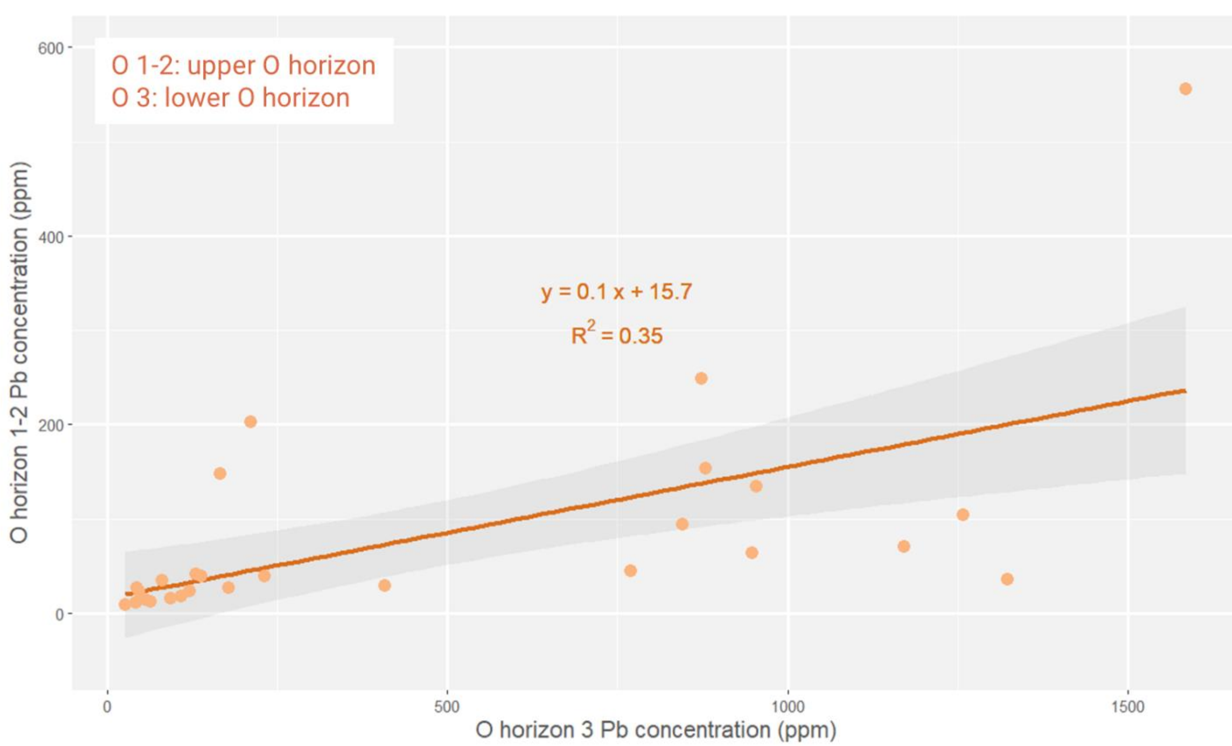

Figure 14: Graph of upper O1/O2 horizon Pb concentrations vs. upper O3 horizon Pb concentrations, with the linear regression.

VII. Discussion

Soil Pb:

Our results show that Walltown, East End, and East Durham Parks all have mineral soil Pb well above the geologic background, with many areas exceeding the US EPA's hazard thresholds for gardening (100 ppm), residential play areas (400 ppm), and residential non-play areas (1200 ppm) [22,23]. The Pb levels in the soil samples from our hotspots were elevated when compared to soil samples from a 2021 study by Wade et al., which extensively sampled soil from Pb-contaminated sites across the city of Durham [3]. Our samples had elevated Pb compared samples from street sides and residential yards in Durham, and our samples had similar Pb to samples from residential foundations in Durham [3]. Additionally, the geospatial distribution of soil Pb concentrations demonstrates the complicated land use history of these land parcels, pointing towards multiple sources of Pb inputs and outputs throughout the 20th century. From local newspaper articles, we have direct evidence for the disposal of incinerator refuse on these sites, along with the removal and addition of soil, gravel, and other landscaping materials. While the contamination patterns in our study are clearly related to the historic waste incinerators at these sites, Pb has many other well-known historical sources which could have also contributed to these patterns. Some studies from around the world demonstrate some difficulty in parsing out the sources of metal contamination and the effects of other environmental variables (such as soil type and wind direction) at incinerator site soils [18,57,59,60].

O Horizon Pb:

Our study also demonstrates that hardwood secondary forest O horizons provide a blanket for highly Pb-contaminated mineral soil. However, a significant amount of mineral soil Pb is mixed up into the O horizons, especially into the lower O3 horizons; this layer experiences more bioturbation as uncontaminated organic materials are decomposed into smaller particles and incorporated into the contaminated mineral soil below. Additionally, this barrier depends strongly on the fact that there is a sustained and substantial input of leaf litter and other plant debris, and that this organic matter then remains in place without disturbance. Organic matter is not necessarily a stationary or robust layer, and it is prone to many disturbances from both humans and the natural environment, which can create a direct pathway of exposure to contaminated soil below. This highlights the limitations of phytostabilization as tool to reduce Pb exposure, particularly in hardwood forests where there is relatively rapid decomposition and bioturbation in the O horizons compared to some coniferous forests.

VIII. Conclusion

Our main conclusions were:

3. Mineral soil Pb concentrations across Walltown, East End, and East Durham Parks are elevated above both geologic background levels and several EPA hazard thresholds, especially in some highly-trafficked areas.
4. Hardwood forest organic horizons provide a blanket for highly Pb-contaminated mineral soil, but a significant amounts of mineral soil Pb is mixed up into these O horizons. Thus, exposure risk is not eliminated and can remain quite high.

Significance:

The highly-contaminated and high-use areas in our study, such as the southeastern portion of East Durham Park, need to be remediated. Surrounding areas, such as those near the southeastern boundary of East Durham Park along East Main St., should be sampled for soil Pb contamination as well, and exposure monitoring for residents may also be beneficial. Based on historic newspapers from five cities across the USA, many municipalities may have public parks with contaminant metals from historic waste incineration, posing a similar exposure threat to residents.

Additionally, the urban parks in our study provide countless services to the Durham community, and the forests within them have great potential for management activities that would further increase their value as natural areas. They are ideal targets for invasive species management and increasing trail connectivity throughout the city, but these activities should be guided by knowledge each park's history, particularly the contamination and subsequent exposure risks for the people who would manage and use the parks.

Future Recommendations:

Going forward, I suggest exploring the vertical distribution of soil Pb at these sites through soil coring, as this can give greater insight into the exact land use history and how this impacted soil Pb accumulation throughout the last century. I also recommend comparing hardwood and conifer O horizons in terms of their ability to provide a barrier to Pb exposure from contaminated soil. Conifer litter decomposes much more slowly with less bioturbation, allowing thicker, denser layers to accumulate on the forest floor. Thus, it may be expected that Pb is mixed up into the O horizon less in a conifer forests than hardwood forests. This kind of comparison can be carried out with other plant types and ecosystems as well.

I also suggest sampling mineral soil and O horizon Pb at Lyon Park, which was also a historic waste incinerator site but was left out of our study due to time constraints. This park also has a riparian zone and a large area of unmanaged forest in and around the old incinerator site. Additionally, other parks such as Northgate Park received ash and cinders as fill from the historic incinerators during their construction in the 1950s [55]. These should also be sampled for mineral soil and O horizon Pb contamination.

The areas surrounding the newer centralized incinerator in northeast Durham should be sampled, especially the adjacent, low-lying swamp in which ash and cinders were dumped throughout the lifetime of the facility [53]. This incinerator was sited in this location in part because of this potential dumping area just north of the incinerator, which is likely to be very high in many heavy metal contaminants [40,53].

Additionally, a more controlled experiment or study should be done that corrects for the highly variable land use history and Pb inputs present in our study areas. It should use study areas that have had the same type and amount of Pb inputs over the same time frame and have not been affected by different human activities since that time.

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