Legacies of Lead Paint Contamination in the Mineral Soils Adjacent to Historic Buildings

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April 28, 2023

Masters project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in The Nicholas School of the Environment of Duke University

Executive Summary

For hundreds of years, compounds containing the element lead (Pb) have been added to paint in order to improve the texture and weather resistance. Across the United States, millions of homes and buildings were painted with lead-based paints up through the 1970s, when lead paint was phased out following medical research confirming the link between lead and a variety of neurological and developmental disorders. Over 170 million Americans are estimated to have been exposed to lead levels above safe concentrations, many of whom were likely exposed to soil lead while playing in yards as children. Although the phase-out of lead in paint began over 50 years ago, the legacies of contamination from lead paint are still present in the soil in a meaningful way. This is largely due to the immobile nature of lead in the soil, tightly binding to clays and other particles, preventing it from being leached out of the soil.

Previous soil lead studies have attempted to characterize spatial patterns of contamination at various scales, but this study is unique in the highly fine-scale sampling design around each structure. Up to 190 samples were taken around each structure, at a point density of 1 sample every 4-12 square meters, prioritizing areas closer to the base of the structure. Nine study sites were chosen in the vicinity of Durham, North Carolina, including 2 buildings that continue to be well-maintained, 5 dilapidated structures, and 2 footprints of buildings burned to the ground. For our study, we surveyed the top inch of the mineral soil using an Olympus Vanta portable X-ray Fluorescence Machine to get lead concentration in parts per million.

At all nine of our study sites, we found evidence of elevated lead levels in the mineral soil that can reasonably be attributed to legacies of paint contamination. Sites varied in the intensity of lead contamination, ranging from maximum values below 300ppm to multiple samples above 5000ppm, and each had its own unique footprint of soil lead. Interpolations of lead concentration were created in ArcGIS from the point data. Despite the variation, we were able to draw a variety of conclusions about the state of soil lead around historic structures:

- Concentrations are typically highest adjacent to the base of the structure, and often decline rapidly with distance.
- Concentrations often decline back down to the geologic background within 4-12 meters of the structure, related to the maximum concentration.
- The corners of buildings are often hotspots for lead contamination, likely due to weathering patterns of paint.
- Topography and erosion of soil can affect concentrations and directionality of elevated lead plumes.
- We did not find any direct pattern between lead levels and a building's height, age, location, or level of maintenance.
- Destroyed/burned structures can show very high hotspots even within the footprint of the former structure.
- Mulch and other ground covers may either protect the soil from contamination or insulate the soil lead from loss.

Statistical and geospatial analysis was used to help characterize the spatial patterns of the contamination at each site. For each structure, data of lead concentration versus distance from the building was used to generate a logarithmic regression that can be used to predict concentration at any given distance. For two structures, interpolations were georeferenced to estimate the area of spatial contamination at different thresholds. Other analyses were done on a site-specific basis, such as comparing concentrations at the different cardinal directions from one structure.

All of our results were communicated and interpreted to the landowners to help inform their knowledge of their properties. This is especially important considering most of our sites are open to the public, and multiple have outdoor programs for children. For each site, we estimated a total health risk, based on the levels of lead contamination and the potential for human exposure. Considering the levels still present in soils even after 50+ years, more research is needed into soil remediation methods, as the high values we found in soils demonstrate that lead still poses a considerable risk to humans.

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Introduction

Today, the element lead (Pb) is commonly known as a dangerous and toxic environmental contaminant with the potential to cause adverse human health effects even at low levels. However, this has been a fairly recent revelation, with widespread use of lead in consumer products continuing well into the 1970s. Current research estimates that 170 million living Americans were exposed to lead in childhood, at levels that today are considered dangerous (McFarland et al 2022). The National Institute of Environmental Health Services states that no blood lead level is safe, meaning that lead exposures cause adverse physiological responses even at very low doses (NIEHS 2022). Fortunately, the CDC estimates that only 2.5% of children have a blood lead level above 3.5 micrograms per liter. For children with blood lead levels below 5 micrograms/liter, effects can include decreased IQ, academic achievement, and increased problem and attention-seeking behavior. The McFarland study estimates that lead has caused a total loss of over 824,000,000 IQ points across the country as of 2015, or 2.6 IQ points per person. For adults, this low-level contamination can lead to kidney problems and decreased fetal weight in pregnant women. At blood concentrations up to 10 micrograms/Liter, children can also experience decreased hearing and reduced postnatal growth, as well as delayed puberty. At this level, adults may experience high blood pressure and hypertension, with increased incidence of essential tremor. Problems continue to compound as concentrations increase, including cardiovascular and nerve disorders, as well as reduced fertility. At extreme levels, acute lead poisoning can cause extreme abdominal pain and even death (Gopinath et al 2021).

The large numbers of Americans exposed to lead contamination would naturally beg the question, where is this contamination coming from? Before the above health effects were well understood, many household products contained lead (CDC 2023). Lead can be used as a softener in plastics, which means it may be found in toys (especially that are produced in other countries or passed down through generations). It may also be used in alloys in jewelry or other products. Another potential avenue of contamination is through drinking water, as lead may be found at the bottom of wells or in older municipal water pipes that are not properly treated. This latter example became headline news in the United States when lead was found in Flint, Michigan's drinking water supply in 2014 (Olson et al. 2017). This latter study brought to light the environmental justice concerns affecting how response and remediation vary depending on the racial and socioeconomic standing of affected communities. Other studies have confirmed that disproportionately high lead levels in soils can also be found in underrepresented neighborhoods of cities (O'Shea et al. 2021).

The two most common forms of lead contamination in the USA are from gasoline and paint. Lead was originally added to gasoline in the 1920s when it was found to reduce engine knocking and help automobile engines run more smoothly (Yvette 2021). Beginning with the Clean Air Act of 1970, the USA began phasing out leaded gasoline, a process that wasn't fully completed until 1996. The lead in exhaust emissions from vehicles mixed with the roadway atmosphere and most settled in nearby soils less than 10s of meters from roadways. Because of this, urban areas and major highways often show a gradient of lead contamination highest at the immediate roadsides, but elevated levels can persist many meters away (Wade et al. 2022). Lead in paint dates back to the ancient Greeks and Romans, and was widely used in the USA beginning in the Colonial Era (ULPL 2019). Lead made paints more durable and washable, and so was in very high demand well into the 20th century, with even the federal government formally recommended suspending its use. Beginning in the 1930s and 40s, scientists began to make the

connection between lead and health issues, leading to a decline in popularity of lead-based paint, especially with the development of new alternatives. In the 1950s, many cities banned the use of lead paint on interior surfaces, which helped curb incidents of children exposures, including eating flakes of the sometimes sweet-tasting lead paint (Hauptman et al. 2017). In 1971, Congress passed the Lead Poisoning Prevention Act, which mandated that the Department of Housing and Urban Development take steps to prohibit use of lead paint in any federally-built residences (Ettinger et al. 2019). By the time the government officially banned the sale and use of lead paint in 1978, it had already been phased out in the market.

Of course, just because application of lead paint stopped in the 1970s, it doesn't mean that contamination stopped. The durability of lead paint (once its most desired quality!) means that it persists on structures for decades and even centuries. Even as of 2018, the Department of Housing and Urban Development estimated that roughly 35% of American homes contain some amount of lead-based paint (GAO 2018). As weathering of these homes continues, lead paint will continue to flake off and break apart often making its way into household dust and the surrounding soil. Because of this, lead contamination continues to be a real danger across most of the United States, especially for children who are both at higher risk physiologically and more likely to be playing in such soils.

Historically, soil scientists have tended to focus on soils as a natural body, and neglected study of the anthropogenic effects on soil, including humans as a soil forming factor (Richter 2020). As pedologist Dan Richter writes, "How ironic that the soils of our front- and backyards are a soil-science frontier!" Historic soil mapping efforts, including the USDA's Web Soils database, often list soils in developed areas only as "Urban Soil Complex" without sampling or reporting much soils data. However, interdisciplinary groups of scientists have been working to understand the unignorable ways in which humans have altered the entirety of the Earth, with some characterizing humans as Earth's primary geomorphic agent (Hooke 2005). This realization has led many to refer to the current era of Earth's history as the "Anthropocene" (Crutzen & Stoermer 2002).

With a few exceptions, it has not been until fairly recently that the soil scientists have come to incorporate human influences into their understanding of soil formation and health. In 2014, the 12th edition of the NRCS Keys to Soil Taxonomy began describing and classifying human influences on soil, even featuring photographs of a variety of altered soils on its cover (Richter 2020). Under the natural-body concept of soils, there are five commonly agreed-upon soil forming factors: Climate, Parent Material, Topography, Biota, and Time. However, in many urban soils, it is clear even to the untrained eye that the soils present have been greatly affected and even created from human influence. Some soil scientists accept humans as a sixth soil-forming factor, or at the very least a control on the other five (Dudal et al. 2002). Certainly, the dearth of research on urban soils means that there is limited understanding of how urban pollution interacts with the soils present, which could cause scientists and public health officials to underestimate risks posed by soil contamination.

Lead ores are found naturally in Earth's crust, in several different chemical compounds (PAHO 2013). Common compounds include, for example, lead sulfide (galena), lead sulfate (anglesite), lead carbonate (cerrusite), lead chloroarsenate, and lead chlorophosphate (pyromorphite). The geologic concentration at a given site will vary by the bedrock type and characteristics, but the overall "geologic background" concentration for lead is generally considered to be around 0.002%, or less than 30 parts per million. At this background level, lead does not pose a serious risk to human health, but soils are capable of holding

high concentrations of lead through adsorption to clay and organic matter (Chaney et al. 1989) and via precipitation to insoluble compounds. Typical soils can hold over 10,000 mg of lead per kilogram, via adsorption to clay minerals and metal hydroxides. In all of its forms, lead is very immobile in soils, though the predominant species present will depend on the characteristics of the soil (Kicinska et al. 2022). At pH above 6.5, it will be most commonly precipitated with carbonates and phosphates, while in acidic soils it may be found in organic complexes, with carbonates ($PbHCO_3^+$), or as a free ion (Pb^{2+}). In alkaline soils, lead hydroxide ($PbOH^+$) is present with lead carbonate ($Pb(CO_3)_2^{2-}$) present as well.

However, anthropogenic lead may enter the soil as a variety of other compounds, some of which may not be found in nature. Leaded gasolines put lead into the environment in the forms lead chloride bromide (PbClBr) and lead sulfate ($PbSO_4$) (Cheney 1989). Lead paints, however, contained lead in the form of a carbonate ($PbCO_3 \cdot Pb(OH)_2$) and lead chromate ($PbCrO_4$). In the common vocabulary, lead carbonate is referred to as "white lead," while lead chromate is referred to as "yellow lead" (PAHO 2013). Lead tetroxide (PbO_4), referred to as "red lead," may also be found in paint. The lead from the paint will enter the soil over time as it flakes off the house, or through other ways such as paint stripping/sanding, or even burning of the structure. Once in the soil, the lead will interact with other compounds present and can change form, often controlled by pH and other physical characteristics of the soil (Kicinska et al. 2022). In most forms found in the environment, bioavailability of lead is high- for example, 50-80% of lead ingested by humans will be retained (Chaney 1989).

This study builds upon and draws inspiration from previous Durham, NC lead soil studies. Of particular importance to our study was Anna Wade and Daniel Richter's 2019-2020 research that resulted in the paper "Urban-Soil Pedogenesis Drives Contrasting Legacies of Lead from Paint and Gasoline in City Soil." In this paper the authors explore the concept of anthropedogenesis (humans as soil forming agents) through the lens of historic lead paint and leaded gasoline contamination of Durham's urban soils. Interestingly, despite the large quantities of leaded gasoline deposited (2000-3000 metric tons) between 1950-1982 in Durham NC, the study found that on average, the soils sampled within 1m of home foundations exceeded the soils sampled within 0.5m of roadsides, averaging 649ppm and 150ppm respectively (Wade et al. 2021). While this study was extensive, covering an impressive area of $35km^2$ of land and sampled 62 randomly selected homes in Durham's oldest neighborhood, the study lacked the fine scale resolution necessary to detail how exactly anthropogenic soil lead persists in our landscape. With the Wade and Richter study finding alarmingly high levels of Pb within 1m of older Durham house foundations, our work endeavored to build upon Wade and Richter's research to provide a fine scale resolution understanding of soil lead's persistence and footprint around historic Durham structures.

Another recent study by Enikoe Bihari and Daniel Richter investigated legacies of soil lead contamination in Durham city parks, resulting from waste incineration facilities operating at these locations through the mid-20^{th} century (How to cite?). A portable XRF instrument was used to sample the top inch of the mineral soils at sample points scattered throughout the various parks, in order to generate an interpolation map of lead concentrations throughout the park. With roughly 100 points in each ~5-hectare park, this study provided finer scale sampling than most previous urban lead studies. Not surprisingly, lead hotspots were typically found in the vicinity of the old incinerator locations, with levels occasionally exceeding 1,000 ppm. Areas that had undergone soil transformations, such as on a baseball field, tended to have low concentrations. Since these sites are now public parks, there is a high potential for exposure of children to the soil, suggesting a need to investigate remediation options.

Elsewhere around the world, environmental scientists and toxicologists have studied urban soil lead in a variety of different ways, primarily at relatively coarse city- or neighborhood-scales. Examples of intensive, building-scale soil lead sampling are rare in the literature, and represent a new avenue of exploration, with significant implications for exposure risk and remediation potential. In 1989, Chaney et al. published a review of soil lead mobility, which included a survey of lead around a single building. On three different sides of a 100+ year old home in Maryland, soil was sampled at 1 meter distance from the house, 5 meters, and 10 meters. In surface soil within 1 meter of the house, lead concentrations were 1050ppm, 7330ppm, and 44700ppm (nearly 4.5% lead!). Further from the home, surface soil concentrations were lower. Samples were also taken at depths of up to 15cm. At 5 of the 9 survey points, one of the two subsurface samples were higher than the surface sample, showing the potential for downward movement of lead in the soil due to pedoturbation. Each sample in this study was comprised of ten subsamples that were averaged together, meaning that it only hints at a true spatial pattern rather than truly showing one. No doubt the intensive process of calculating lead concentrations in soil would have made a larger-scale project more difficult (samples were collected and brought back to the lab, dried, sieved, and extracted using nitric acid).

It is also relevant to consider soil lead studies done at larger scales, as these help contribute to our knowledge of lead distribution in cities. Solt, et al. (2015) studied spatial patterns of soil lead in Sacramento, California. This study collected samples at 91 points around the city, and analyzed them in-lab using a combination of chemical extraction and X-ray fluorescence. Highest lead concentration levels were found in the urban core of the city, where there would have been the highest density of cars leaded gas aerosols. A heat map of lead concentration in the city was generated using interpolation from the points (Schwarz et al. 2012). This team did relatively fine-scale sampling of residential parcels in Baltimore, Maryland, using portable X-ray Fluorescence, and found that over 30% of the parcels had averaged soil lead measurements above 400ppm. Over half of the parcels surveyed had at least one measurement above 400ppm, and strong correlations were found between soil lead and building age, distance to roadways, and distance to the built structure. Hartikainen and Kerko (2009) investigated soil lead at depth in a Finnish shooting range, and found an average downward migration of lead at 2-3mm per year, with the highest concentrations remaining in the forested O horizon of the coarse-textured Entisol. In the older part of the shooting range, concentrations at depth were as much as 10x greater than in newer parts, demonstrating the potential for slow transport over time.

The goal of our study is to better understand the spatial distributions of soil total lead around structures that have previously been painted with lead-based paints. To do this, we used a unique sampling design that captures fine-scale differences in soil lead concentration via portable X-ray fluorescence. Nine structures were chosen in Durham and Orange counties, North Carolina, with the goal of including a variety of structure types, uses, and ages. Specifically, our structures are: 1) standing and well-maintained to the present, 2) standing but dilapidated due to years of limited care, or 3) destroyed by fire but with known footprints. See the methods section below for a full description the 9 sites. Variation between the sites will be compared quantitatively and qualitatively, incorporating notes made during our site visits.

The key product of this study will be interpolation maps, showing each structure individually, with sample point concentrations shown, and a heat map around the structure made via interpolation. These maps will be useful for visualizing and interpreting spatial patterns of lead contamination, and characterizing risk to humans and the environment. Our maps and figures will also help inform and

guide efforts for soil remediation, by illustrating the distribution and extent of soils that may need to be treated in some manner before they can be considered safe.

Methods

Sampling Design and Field Techniques

In order to capture fine scale resolution of soil lead at the nine sites, we used transects to create a systematic grid of sampling points around each of the structures. The transects were evenly spaced around the perimeter of the structure at a 2m or 3m interval depending on the size of the building. Each transect had standardized spacing for the sampling points, radiating out perpendicularly from the structure's foundation. In general, the spacing along each transect followed a consistent 0.5m, 2m, 4m, and 8m distance from the structure's foundation, yet there was some variation between and within our study sites depending on building footprints and site limitations. Examples of site limitations that required adjustment of spacing along our transects, included surfaces lacking sampleable mineral soil such as gravel or cement roads and sidewalks. In such instances, we sampled near to the gravel or cement sidewalk as possible while trying to stay as true as possible to our standardized transect interval. In addition, for sites where the structure had burned to the ground at Nettie's House and the Eubanks historic church, our transects were oriented within the suspected footprint of the no longer standing structure as well as radiated out from the old foundations. Ultimately, our justification for utilizing evenly spaced transects to create a grid around each structure was that this method allowed us to gain insight into the gradient like nature of lead contaminated soil surrounding old buildings and according to the EPA, grid sampling is a preferred method for identifying areas of contamination (EPA 2022). In addition, the grid spacing could be replicated and adapted for each site allowing for comparable fine scale resolutions across each study site.

We maintained consistent techniques when building the grids, preparing the soil samples, and running the XRF machine in the field. After surveying each site in the field, we would sketch the footprint of the building and mark out our transects following standardized spacing. Once the building's footprint and the sampling grid were measured and sketched, we marked the nodes of our grid using meter tapes and pin flags. At each pin flag, we prepared the soil by homogenizing the top 2.5-cm of mineral soil making sure to clean the hand trowel after each preparation. After the soil was prepared, we operated the XRF on the soil taking note of the Pb concentration, sampling location, date, and corresponding XRF code.

Our portable XRF instrument (Olympus Vanta M) functions by emitting X-rays into our prepared mineral soil causing the elements in the soil to fluoresce and travel back to the machine's detector allowing the machine to count and estimate Pb (mg/kg) for each sample location. We ensured high performance of the XRF by calibrating the XRF in the field with a blank and two standards as per the manufacturer's recommendation.

Historic Structures

In many ways, soil tells the story of a landscape and its inhabitants. It is active—constantly interacting with plants, animals, humans, and the environment. It is "the great connector of life and destination of all" (Berry 1977). In this vein, the history of each of the seven sites that we sampled is integral to the

character and the composition of the soil. While some of the stories of these sites and structures have been lost and erased by time, distorted by romanticized narratives, or silenced by colonial harm, the authenticity of place lives on in the soil. Even though it is out of the scope of this paper to provide a researched and thorough land history of each site, our study illuminates the harm caused by colonialism and industrialization reflected in toxic lead that lingers in the soil. Sadly, as soil is the "great connector of life", it also lingers in our bones with lead contamination in modern adults in the United States being nearly 1000 times greater than pre-colonized Native Americans (Berry 1977; Ericson et al. 1991). Our research on the fine scale resolution of lead provides a snapshot into an era when the United States was a nation of "white leaders," and even though "they knew that 'white lead is a poison'... they believed that their industrializing world demanded white lead" (Warren 1999).

Nettie's House

Mary Annette (Nettie)~~.~~ Couch was born in 1866 and died in 1965 and was the last of the Couch family to live on their family land of two hundred years before it was sold to Duke University in 1947 (Couch 2023; Frankel 1984). "Plagued by thirty years of low prices for his wheat and pork surplus" from 1866-1896, Nettie's father John W. Couch had difficulty maintaining the nearly three-hundred-acre farm (Frankel, 1984). After John W. Couch's death in 1917, Nettie was the last Couch who remained on the family land, and she survived with a humble quilt business and subsistence farming (Frankel 1984). In order to survive and pay property taxes, Nettie rented a room in her house to an elderly lady and rented farm land out to tenant farmers. Nettie eventually fell behind in paying her property taxes and to encourage her sale of the land, Duke University offered to pay the back taxes for the Couch Family and promised that any member of the Couch family could remain on the land with the transfer of the property "made subject to the life estate of Mary Annette Couch" (Frankel 1984).

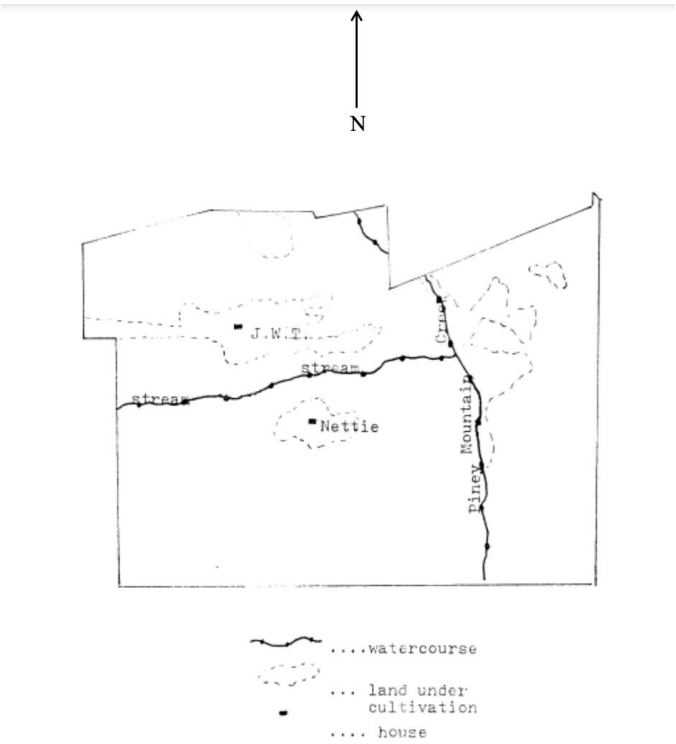

Figure 1. “Nettie’s House” and cultivated area circa 1915 provided by Rachel Frankel

Today, it is hard to find Nettie’s House as it is hidden deep in a little visited section of the Duke Forest. Nettie’s House was likely built around the turn of the 20th century and it burned to the ground sometime in about 1990 (Daniel 1994). It was likely built as a two-story wood-framed and clad farmhouse with two exterior chimneys typical of the era and place. According to Daniel, the original footprint was thirty-four feet by 16 feet which is comparable to our findings in the field (Daniel 1994). What was once the lifelong home to Nettie is now overgrown with wisteria and littered with rubble and bricks. One chimney remains standing anchored in place by the wisteria vines. After years of Nettie cultivating crops directly surrounding the house, the site has been abandoned for decades, burned to the ground, leaving space for the forest to reclaim the land.

Figure 2a. Dan Richter tromping through the Wisteria as he marks out locations for soil samples at "Nettie's House."

Figure 2b. "Nettie's House" circa 1994 provided by Randolph Daniel Jr.

Broken Spoke Farm

"No pesticides, No GMO, ALL LOVE," Broken Spoke Farm is a small family run farm that functions in opposition to the culture of contamination and commodification on which large scale agribusiness relies (Broken Spoke, 2023). Located at the corner of St. Mary's Rd and Pleasant Green Rd in Hillsborough, NC, Broken Spoke Farm grows and sells organic produce. At the property's entrance stands a dilapidated farmhouse—a reminder of the Piedmont's agricultural history in which "what ensued, especially in conjunction with slavery, was a system in which exhausted land, rather than being ameliorated, was abandoned or retired from use, where it often eroded profusely before going up in brush" (Trimble 1985). Built in 1929, the single-family wood framed, and clad structure has long been abandoned, as the rotting wood sill beams precariously span from one crumbling brick pier to another.

Image 3. Farmhouse at Broken Spoke Farm

There is a palpable dichotomy at Broken Spoke—with farmers committed to "replenishing the Earth" via new agricultural practices vs the walls that are sagging in the old farmhouse as it weathers away (Broken Spoke, 2023).

Catawba Trail Farm

Image 4. Catawba Trail Farm photo via https://www.youtube.com/watch?v=ILWmMxt2aWE&t=824s

Delphine Sellars and Lucille Patterson have for several years been working to create the Catawba Trail Farm, reclaiming land and empowering their community by cultivating a farm space that is founded on values of equal access, environmental justice, environmental stewardship, and racial justice. In many ways, as seen with anthropogenic soil lead caused by legacies of lead paint and gasoline, soil health is

dependent on history and culture. The connection between healing, culture, and land is undeniable at Catawba Trail Farm:

> UCAN Catawba Trail Farm is on land that was part of the greater Stagville slave plantation. It holds much history of our African-American and Native American ancestors and ensuring that the knowledge and skills they passed down to us, are passed down to the next generations. This history includes on-site buildings that UCAN is in the process of repurposing and preserving. We also plan to construct new and necessary infrastructure (UCAN 2023).

We sampled soils surrounding the three historic buildings that are being reclaimed—transformed from structures of oppression under the Stagville Plantation regime into structures of community empowerment and healing under the care of Urban Community AgriNomics (UCAN). The first structure encountered when entering the property from the west is the old barn. Wood framed and clad with board and batten siding, the paint is highly weathered and many of the structural members are rotting. The northern gable wall is unsupported and sagging. While the structure might appear to be daunting and imposing in its current condition, Sellars and Patterson have plans to transform the old, dilapidated barn into the Catawba Trail Farm welcome center.

The structure to the east of the large barn is a corn crib—a small structure that once functioned as a drying location for grain. While we categorized the corn crib as dilapidated, some work has been done to restore the small structure including new decking and mulching around the perimeter of the structure. The open-air design typical of a corn crib and the large overhang roof supported by cedar logs fosters an inviting gathering space and is planned to function as Catawba Trail Farm's Intergenerational Building.

Finally, the easternmost building on the property is an old millhouse. While the wood siding on the exterior walls of the structure is highly weathered, significant renovations have taken place at the old millhouse. There is a new metal roof, and the interior has been shored up and reframed—complete with a new loft space. We decided to classify this structure as dilapidated as the exterior siding is comparable to the exterior walls of the other dilapidated buildings we sampled. Once renovations are complete the millhouse will function as the farm's educational/demonstration space complete with a functional traditional kitchen to teach valuable kitchen and cooking skills. To the east and north of the millhouse are two large fields in which community members grow food and keep chickens.

Catawba Trail Farm speaks to the power of community, and the connections between healing, culture, and land perhaps provides insight into the remediation of soil and the remediation of past oppression.

The Hart House

Image 5. The Hart House photo via https://www.loc.gov/item/2017883840/

Built in 1850, The Hart House was originally constructed as part of Stagville Plantation slave dwellings known as Horton Grove (North Carolina Historic Sites 2023). One of the largest plantations in North Carolina, "the Bennehan-Cameron family owned approximately 30,000 acres of land and claimed ownership over about 900 people who were enslaved on the property" (North Carolina Historic Sites 2023). After emancipation, the descendants of Ephram Hart, a formerly enslaved man that the Bennehan-Cameron family claimed ownership over, moved into The Hart House. The Hart family renovated the house and lived on the land for many years.

Today, the structure is preserved in an abandoned and weathered state. It is a small two-story wood framed and clad house with a front porch and two small brick chimneys. Like the dilapidated structures as Catawba Trail Farm, the wood siding at The Hart House is highly weathered and appears to have only one layer of previously applied paint and/or whitewash. Unlike the active land reclamation of the Catawba Trail Farm project, The Hart House is managed by the North Carolina Historic Sites and functions more as a passive historical monument.

The Ark

Funded by Benjamin N. Duke and located on Duke University's East Campus, The Ark was built in 1898. Constructed with lumber salvaged from the old Durham County fairgrounds grandstand, The Ark originally functioned as the Duke University Gymnasium (King 1997). Today, the building is home to the Duke Dance Program and is used by the American Dance Festival.

Image 6. The Ark photo via https://en.wikipedia.org/wiki/The_Ark_%28Duke_University%29

The Ark is a large wood framed and clad building with a footprint of over 20 meters long by 12 meters wide and tall enough to be three stories. It is obvious that the structure has been well maintained over the years with no visible sign of degradation. The original wood siding appears to be thick with multiple layers of paint, indicating that the building has been painted numerous times over the years. In addition to the building's obvious upkeep, the landscaping around The Ark is maintained with shrubbery decorating the perimeter of the structure.

The Bennehan House

Image 7. The Bennehan House image via https://ancientnc.web.unc.edu/colonial-heritage/by-time/antebellum/stagville-orange-county/

> *We are a group of Durham residents organized to establish a memorial located in downtown Durham to honor the people formerly enslaved at Stagville Plantation. Through this establishment, we hope to expand our community's collective understanding of Durham's unique history, and specifically, who gets included in that story. We also hope to bring greater awareness to the Stagville State Historic Site, support Stagville's vast group of descendants in coming together under a common purpose, and help the larger community ponder the ongoing legacies of slavery.* (Stagville Memorial Project 2023).

The so called Bennehan House is a two-story wood framed building complete with multiple chimneys, porches, and old double hung windows. It is the harm and exploitation of colonialism preserved, sitting quietly in the forest cleared space. To the passerby this structure might function to evoke a damaging romanticization of a harmful past. The Stagville Memorial Project aims to tell a more truthful story. In many ways, "…we are at one of those critical moments in American history when we will either double down on romanticizing a false narrative about our violent past or accept that there is something better waiting for us, if we can learn to deal honestly with our history" (Stevenson, 2021).

Sampling the soil at many of these sites feels more than just hoping to learn about fine scale soil lead distributions. The stakes feel higher—what truths can these fine scale resolutions of lead soils tell us about the past and how can soil studies retell harmful romanticized narratives? How can studying the soil expose the harms that colonialism has wrought upon the earth?

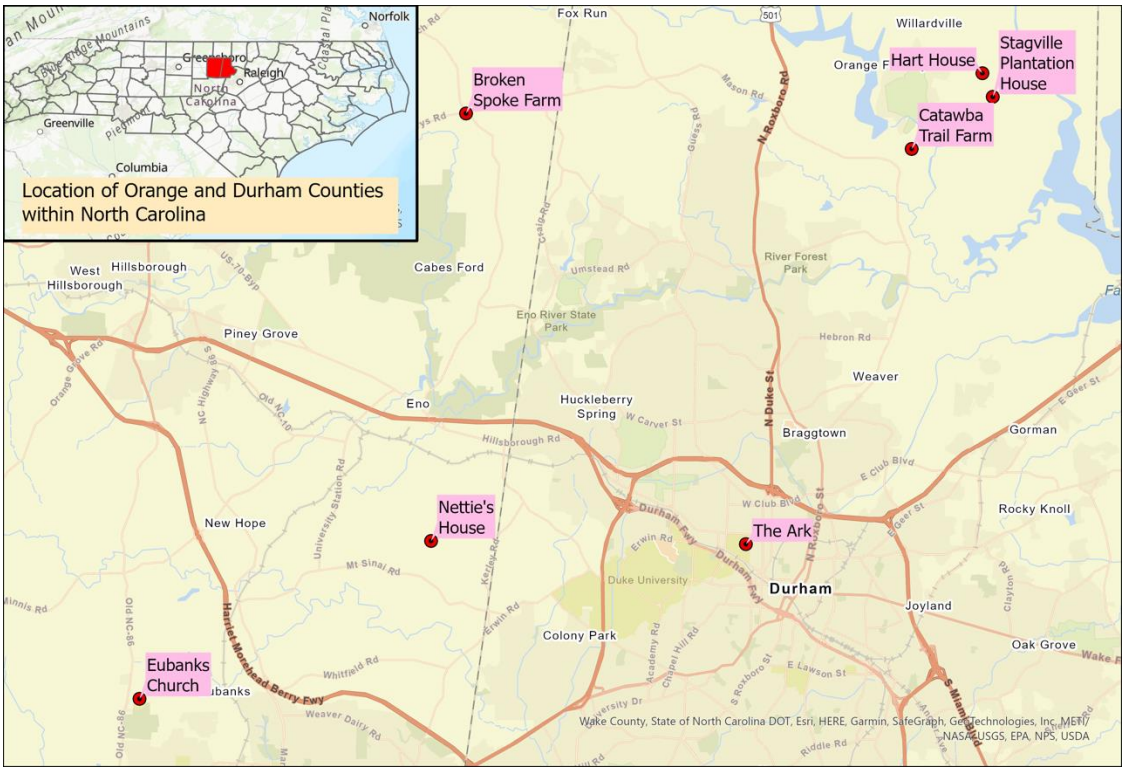

Figure 3. A map of the locations sampled for this study, in Durham and Orange counties, North Carolina. Note that three separate buildings at Catawba Trail Farm were surveyed.

Analytical methods

In the field, detailed notes were recorded about the layout of grid points and the dimensions of the structures, including schematic maps of our field surveys. This allowed us to assign each survey location a sample code along a transect, which then could be matched against the maps to determine the point in space. In an excel spreadsheet, each point was recorded with its code and its lead concentration in ppm, and then given X and Y coordinates based on a Cartesian system we created for each map. This was done by assigning one corner of the structure as an origin (0,0), and then calculating the distance in meters away from the origin of each point, using the maps drawn in the field. Those files were read into ArcGIS Pro using the XY Table to Point tool, and labelled using the lead concentrations (ESRI 2020). Using known distances from the points as well as photographs and aerial imagery, the outlines of the structures were digitized into ArcPro by hand.

In order to produce continuous maps for the entire area surrounding a building, an interpolation was done from our sample points. Many different types of interpolations are available through ArcGIS, and after a visual comparison of multiple methods and a review of benefits and weaknesses, we decided to proceed using the Natural Neighbor interpolation, with the default settings generated by ArcPro version 3.0 (Sibson 1981). There is a long history of Natural Neighbor interpolations being used for a wide range of environmental parameters, including soil chemistry (Mitas and Mitasova 1999). The method works by generating Voroni polygons for each input data point, and then drawing new Voroni polygons for each sample point, e.g., each pixel in the interpolation (Esri 2023). The value assigned to that pixel is calculated from the values of the “neighboring” survey points, which have a weighted influence

depending on the proportion of overlap between the initial and second set of polygons. This method is noted for working well regardless of the distribution of the data, producing smooth gradients, and preserving the value at each point. Additionally, it works only within the range of the data, so as not to produce ridges, valleys, peaks or pits not found in the data.

In order to produce maps that can be readily interpreted for management purposes, a thoughtful color scale is essential. An exploration into symbology was done in order to make decisions on what color scale to use, how many classes best represent the variability, and how to highlight thresholds and key values. The color scheme used for all final maps (in order to compare lead concentrations between sites) broke the scale up into 12 classes: 3 shades of green for values between 0 and 200ppm, 3 shades of yellow for values between 200 and 400, 3 shades of orange for values between 400 and 1200, and 3 shades of red for values above 1200. Recall the EPA safety thresholds of 1200ppm for non-play areas, and 400 for play areas. Survey points are displayed on maps to show the sampling design for each site as well as true lead values. Sidewalks, porches, and other features are hand-digitized in where relevant, using aerial imagery and notes/measurements made in the field.

GIS was also used to estimate the spatial extent of lead contamination around two of our study sites, The Ark and the Stagville Plantation's Bennehan House. To get this spatial measurement, we needed to calculate the area of the soil covered by our sampling/interpolation. This was done by georeferencing each interpolation to its actual site via aerial imagery and ArcPro basemap imagery with buildings already digitized in. Control points were added to the interpolations to match them up with the underlying imagery, adding 8-12 points and aiming for a total error below 10. The buildings themselves and any surrounding impermeable surfaces were then masked out of the raster, and a reclassification was done to give a raster with 4 classes: 0-200ppm, 200-400, 400-1200, and >1200 (figure 2). This created an attribute table with pixel counts for each class, which were then converted to percentage of the study area. The Measure Area application in R was used to estimate the spatial extent of each interpolation in square meters, subtracting out the area of the buildings so that only the soil was included. This gave the total soil area of the study site, which was then multiplied by the pixel proportions to show how many square meters of the study sites had contamination levels above 200, 400, and 1200ppm. Considering the error present in georeferencing the image and hand-measuring areas, these should not be considered exact measurements but likely give a reasonable estimate of the spatial extents.

Figure 4. The interpolation for The Ark, with impervious structures masked out, and georeferenced to the actual location atop the ArcPro aerial imagery basemap. The four color classes correspond to increasing lead levels: Green <200ppm, Yellow 200-400ppm, Orange 400-1200ppm, Red >1200ppm.

The CSV data files we entered were also convenient for analysis in R (R Core Team 2021). As of the writing of this draft, R has been used to investigate statistical patterns among sampling points at The Ark and the Stagville Plantation's Hart house. Data were rearranged into a dataframe containing each sampling point's lead concentration along with its distance from the structure. Boxplots were generated showing the mean and spread of values for a given distance from each building, and visualized using the package 'ggplot2' (Wickham 2016). More analysis using R is expected to be done as we investigate the spatial patterns and statistical trends in our data.

Results

Sampling Results and Interpolations

Each of the study sites will be characterized and discussed separately, and is accompanied by an interpolation map to visualize the extents of lead contamination. In general, the sites can be separated into sites with relatively low-level contamination (no samples >1000ppm: the Hart House, the Eubanks Church, and the three buildings at the Catawba Trail Farm), and sites with high-level contamination

(multiple samples >2500ppm: The Ark, The Stagville Plantation Bennehan home, Nettie's House, and Broken Spoke Farm).

Table 1. Division of sites based on level of soil lead contamination detected.

Moderate-contamination sites	**High-contamination sites**
Definition: <2 samples above 1000ppm	**Definition: at least 2 samples above 2500ppm**
Stagville Plantation's Hart House	The Ark
Eubanks Church	Stagville Plantation's Bennehan Home
Catawba Trail Farm- Intergenerational building	Nettie's House
Catawba Trail Farm- Kitchen	Broken Spoke Farm House
Catawba Trail Farm- Welcome Center	

The Ark

In many ways, the Ark is the centerpiece of the study. More survey points were taken here than at any other site, and nowhere else did every transect have five points, extending out to twelve meters from the building. Along the north face of the building, many of the 0.5m and 2m points are significantly lower than they are on the south face. This could be attributed to the existence of a stony drainage channel draining water downhill to the east, which may have removed lead as it flaked off of the building, rather than allowing it to enter the soil. However, the highest values also recorded here, 5716 and 4964ppm, were along a stony drainage spot that is now covered by a rocky, impervious cover (perhaps to prevent erosion). The very low levels seen further out along the north and northwest sides may be the result of recent construction work in the vicinity- recent aerial imagery shows this ground being torn up and driven over by truck treads. Along the east side, there appears to be a plume of contaminated soil >200ppm that extends downslope as much as 12 meters. We attribute this plume to erosion downhill on a west-to-east gradient, with lead-contaminated sediment being deposited in lower-lying, poorly drained areas to the east of the structure. The crescent-shaped patch of soil on the west side represents a cultivated garden of woody shrubs with intensive mulching. Although a cultivated garden might be expected to have low lead values, the much-painted overhanging stairway and porch appear to contribute a steady stream of contamination to the soil. There has clearly been landscaping done all around the building that influences concentrations, including shrub cultivation and grass-seeding.

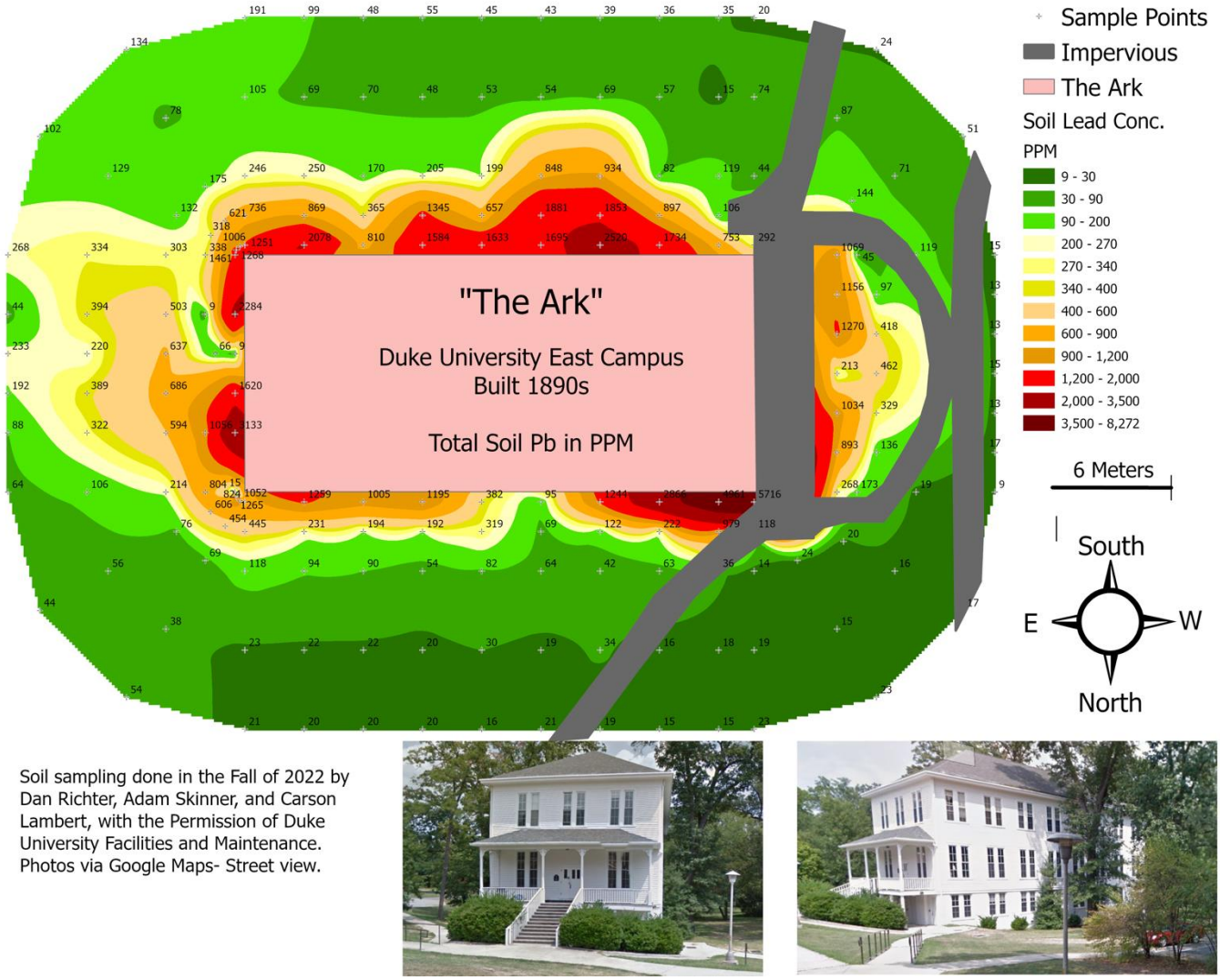

Figure 5. The Ark on Duke University's East Campus, near the center of Durham.

Stagville Plantation- Bennehan House

Our other well-maintained structure is the central plantation home of a North Carolina State Historic Site. Although older and smaller than the Ark, and used for a much different purpose, it is similar in being a multiple story wood frame structure that has been painted many times with white paint. It is likely that multiple storied structures distribute the lead contamination further from the building, as paint flakes may spread farther out into the yard when broken off by wind or rain. This site, along with Broken Spoke Farm, is one of the best examples of contamination hotspots being found in the corners of a building. The two southeast corners both have concentrations above 2200ppm, while the northeast corner has three points exceeding 2400ppm (max = 2676). These points are all in the 'downhill' direction of the local topography, as is the plume of elevated concentrations extending to the southeast. The four soil samples 8-meters from the home in this downhill direction all have concentrations above 250ppm, with the highest being 430ppm. The maximum distance sampled for every transect was 8 meters, which

was not far enough to return to the geologic background (<30ppm) along any of the transects. The four points between the porches on the north face of the building were all within a cultivated garden, which gave some of our lowest readings at this site, unlike at the Ark where the mulched garden maintained high concentrations.

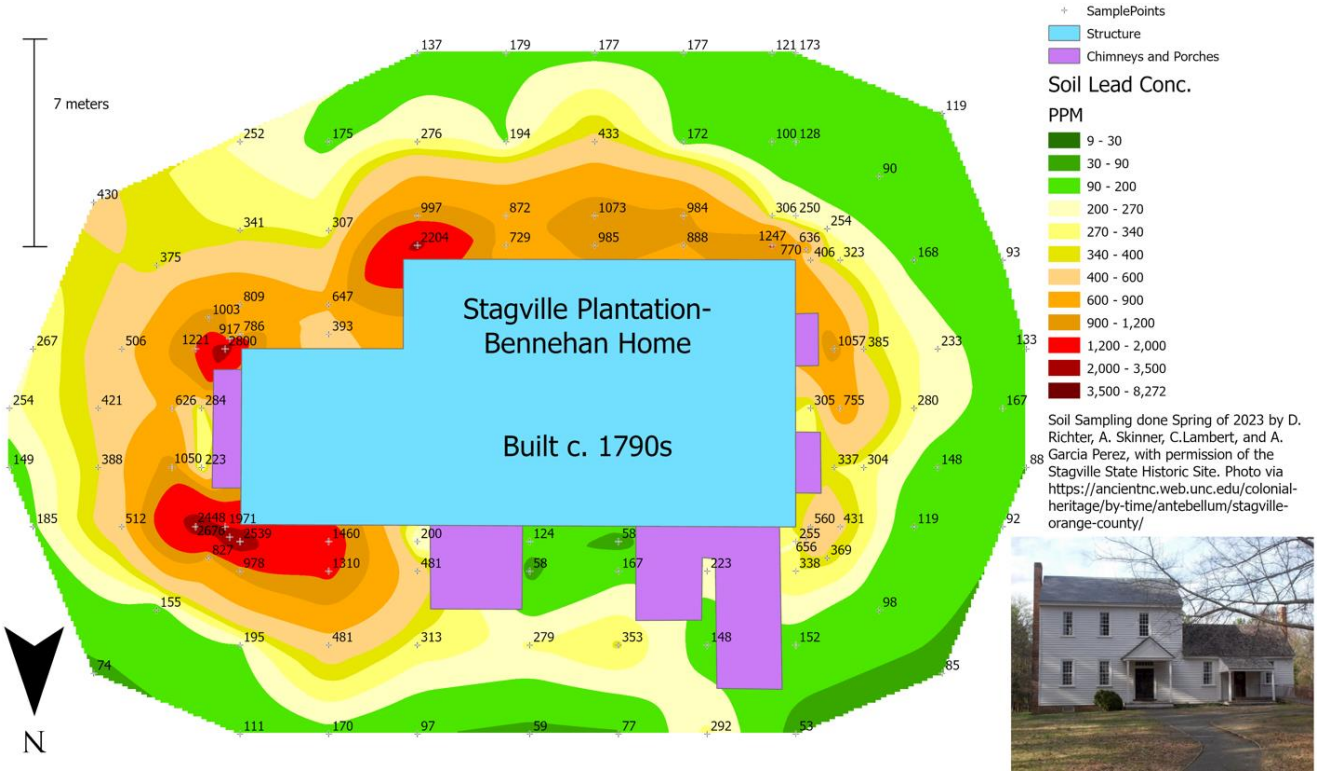

Figure 6. The Bennehan Plantation home at the Stagville State Historic Site in Northern Durham County.

Broken Spoke Farmhouse

This is the first of our five dilapidated sites, although it is alongside an active farm. The photos in Figure 5 show weathered peeling white paint along the house, and perhaps even a formerly interior wall on the north face of the house (brighter white). The map shows very extensive lead contamination around the north, west, and east sides of the house, with hotspots in all four corners. The south side had significantly lower concentrations, which is attributable to a recently added red-clay layer of soil meant for vehicle parking. The northeast corner had some of the highest values we observed at any of our sites: within an area less than half a meter square, we obtained readings of 3887, 5610, and 8493ppm (0.85% total lead). The southeast corner had a hotspot of 3484, the southwest corner had a hotspot of 4042, and the northwest corner had a hotspot of 3871. This phenomenon of corner hotspots was seen at other sites including the Stagville Plantation home, but nowhere is it clearer than at Broken Spoke. On the North side, the plume of lead appears to extend well past the four meters at which we took our furthest samples, with 2 of the four-meter readings above 200ppm.

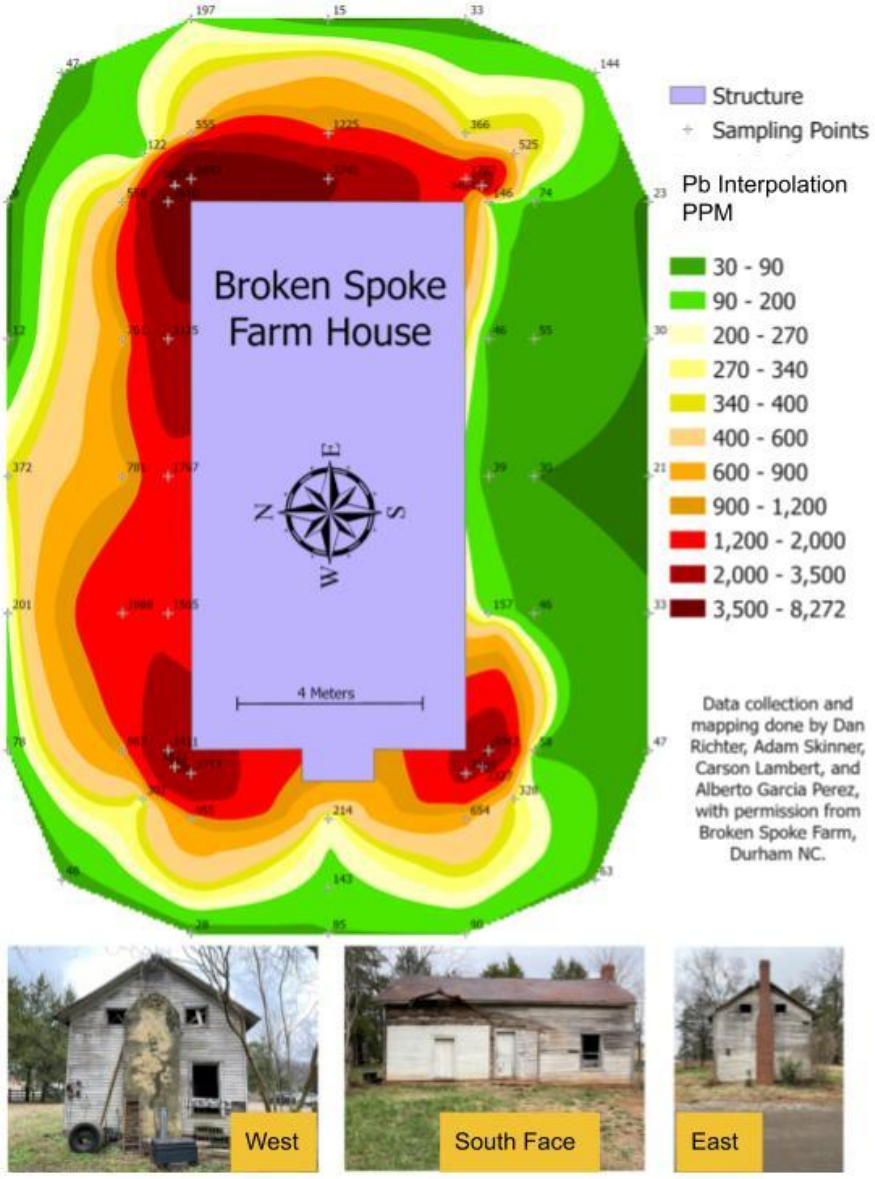

Figure 7. Broken Spoke Farm in rural Orange County. The three photos at bottom, from right to left, show the West, South, and East faces of the house.

Catawba Trail Farm

None of the buildings at Catawba Trail Farm have been maintained for decades, and most or all of the paint was gone from the wood-frame siding. The property and buildings are being upgraded to become the site of Ms. Delphine Sellars' community farm and garden for inner city kids and adults. The first building we surveyed was a former corn crib. This survey was important because of corn crib's planned use as an Intergenerational Building, where there will likely be children who might be exposed to soil contaminants. Soil lead was elevated over geologic background but even at four meters from the building, concentrations were far enough to approach the geologic background. As seen in Figure 8, we

were only able to sample out two meters on the South side of the building, because of the gravel road that ran right along the buildings. On the East side of the building, there is an overhanging roof in front of the porch. Several values were elevated under this roof, with a maximum of 313ppm. Aside from an isolated reading of 345ppm, the only area of concern is along the back of the building, where several high readings were obtained from soil underneath the mulch bed. The highest of these was 758ppm, with an additional 4 readings above 300. Fortunately, the mineral soil in this location is covered by up to six inches of mulch. The mulch beds are illustrated with a dashed line in Figure 6.

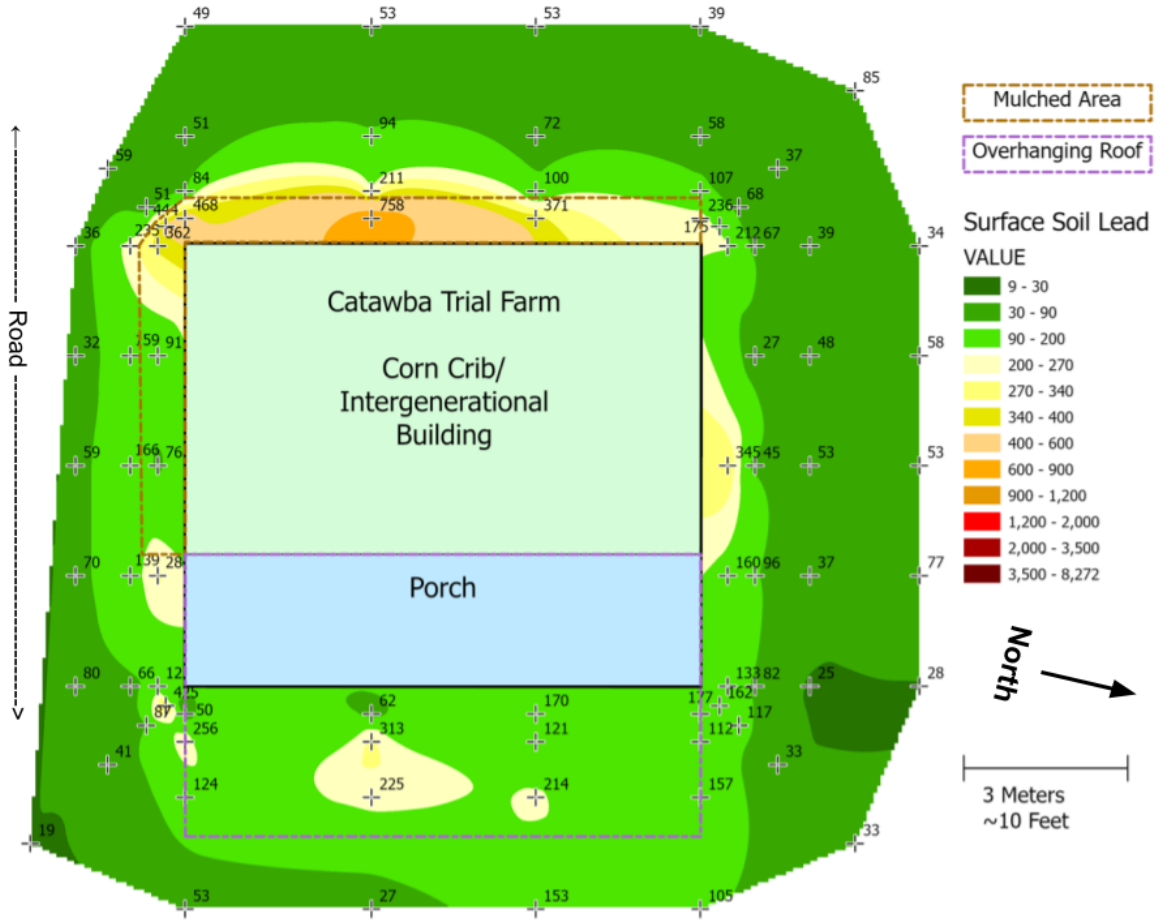

Figure 8. The former corn crib, and planned Intergenerational Building at the Catawba Trail Farm.

The second building surveyed at Catawba Trail farm was only about 20 yards down the road from the corn crib. This was formerly the millhouse, and is in the process of being renovated for use as a kitchen and headquarters area (Figure 7). The structure is surrounded on three sides by an old, partially-decayed bed of mulch that covers the mineral soil and extends roughly a meter out from the building. Much like in the corn crib, this bed of mulch has probably prevented loss or transport of lead-contaminated soils, but also greatly minimizes the likelihood of human exposure. Our highest readings at Catawba were observed along the north side of this building, underneath the mulch bed: 1757 and 1493ppm. Nothing visible to us at the site suggested why this wall of the building might be more contaminated. A few values along the north edge of the mulch bed are concerningly high (>200ppm), as are some along the

south wall of the building where there is no mulch coverage. Otherwise, nearly all of the sample points not covered by mulch were under 100ppm, with a rapid return to the geologic background at most of the four-meter points.

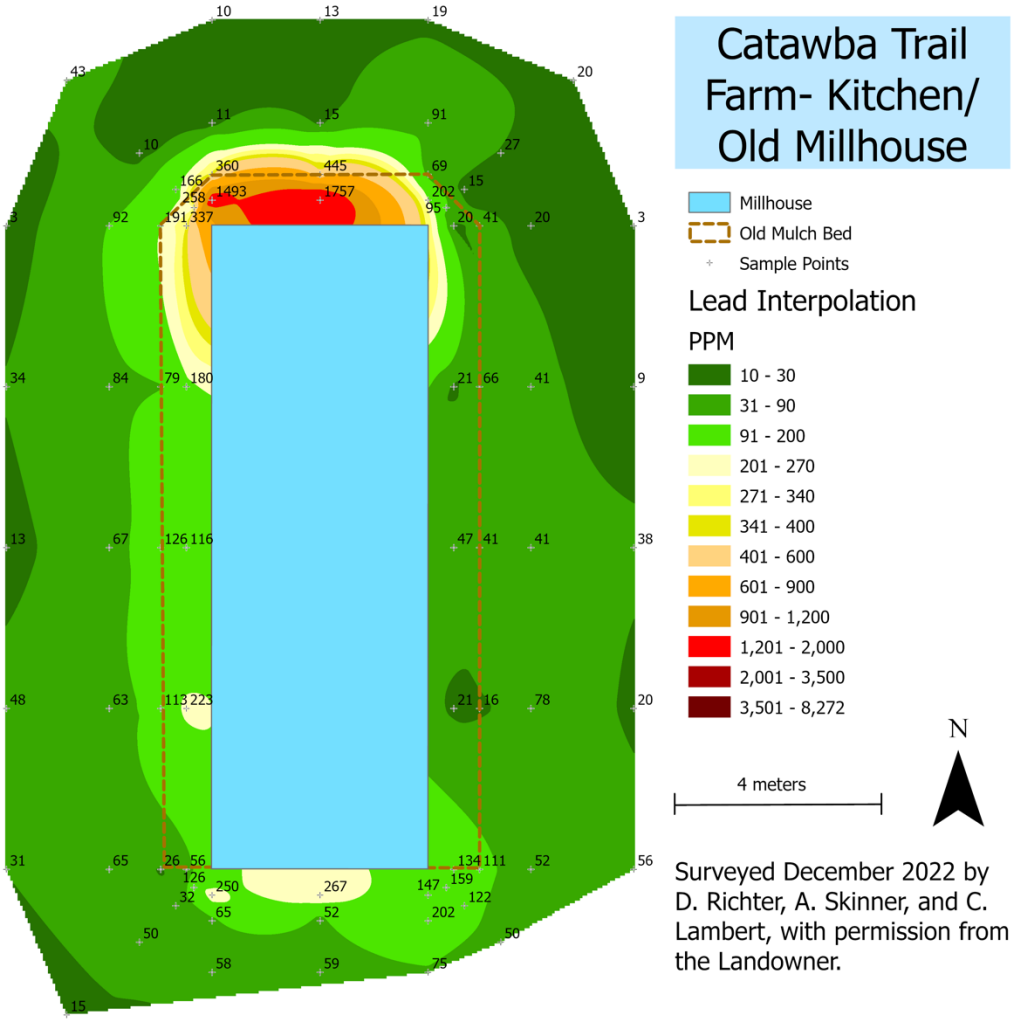

Figure 9. The future kitchen/former millhouse of the Catawba Trail Farm.

The third building surveyed at Catawba Trail Farm was the future welcome center, which was previously used as a barn and storage area, and currently serves as a vulture roost. The barn-welcome center is on the opposite side of as the welcome center (with the corn crib between the two). This is a two-story building with a significant portion of the upper level overhanging an open storage area, bound by the brown dotted line in the figure. The highest concentrations observed here were 594 and 377ppm along the east face, and 309ppm under the middle of the overhanging roof. Scattered points above 200ppm were also recorded along each of the four faces. In general, the highest values appear to be on the east side of the structure, with the overhanging roof also preserving elevated lead levels (perhaps in part due to the painted machinery and detritus that are still stored underneath it. Continued mulching around the building could help prevent exposure to the most contaminated mineral soils, just as it would around the other two buildings at Catawba Trail Farm.

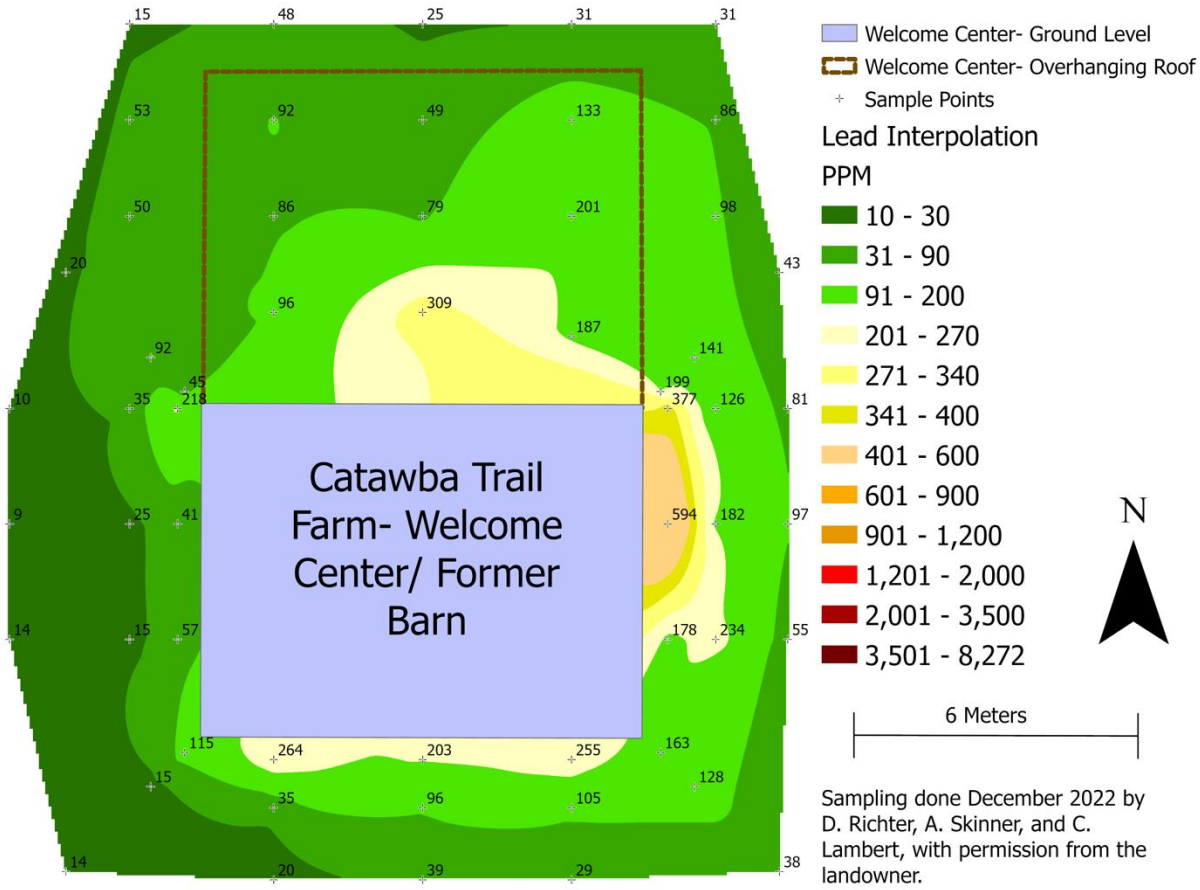

Figure 10. The former barn, and future welcome center at the Catawba Trail Farm.

As an additional exploration, 34 randomly selected points were surveyed throughout the grounds of Catawba Trail Farm. This included areas of cultivated grass, garden beds, and forest-adjacent sites. The mapped points were collected by cell phone GPS and should be considered accurate to within 5 meters. Figure 9 shows an interpolation from these points, illustrating the overall low values that would be expected in soils that don't have a clear legacy of contamination. The northeast side of the property all has values within the geologic background range- this is important because this is where the garden beds and the poultry coops are located. Nearer to the buildings, there are some values that are clearly elevated, interspersed with low values. The highest readings of 202 and 184 were found north of the corn crib, and could result from a historical gasoline or paint spill that is no longer visible today. Looking at the building specific interpolations overlain on the map, one takeaway is the localized nature of the contamination around the historic structures and the role that mulching can play in remediation...

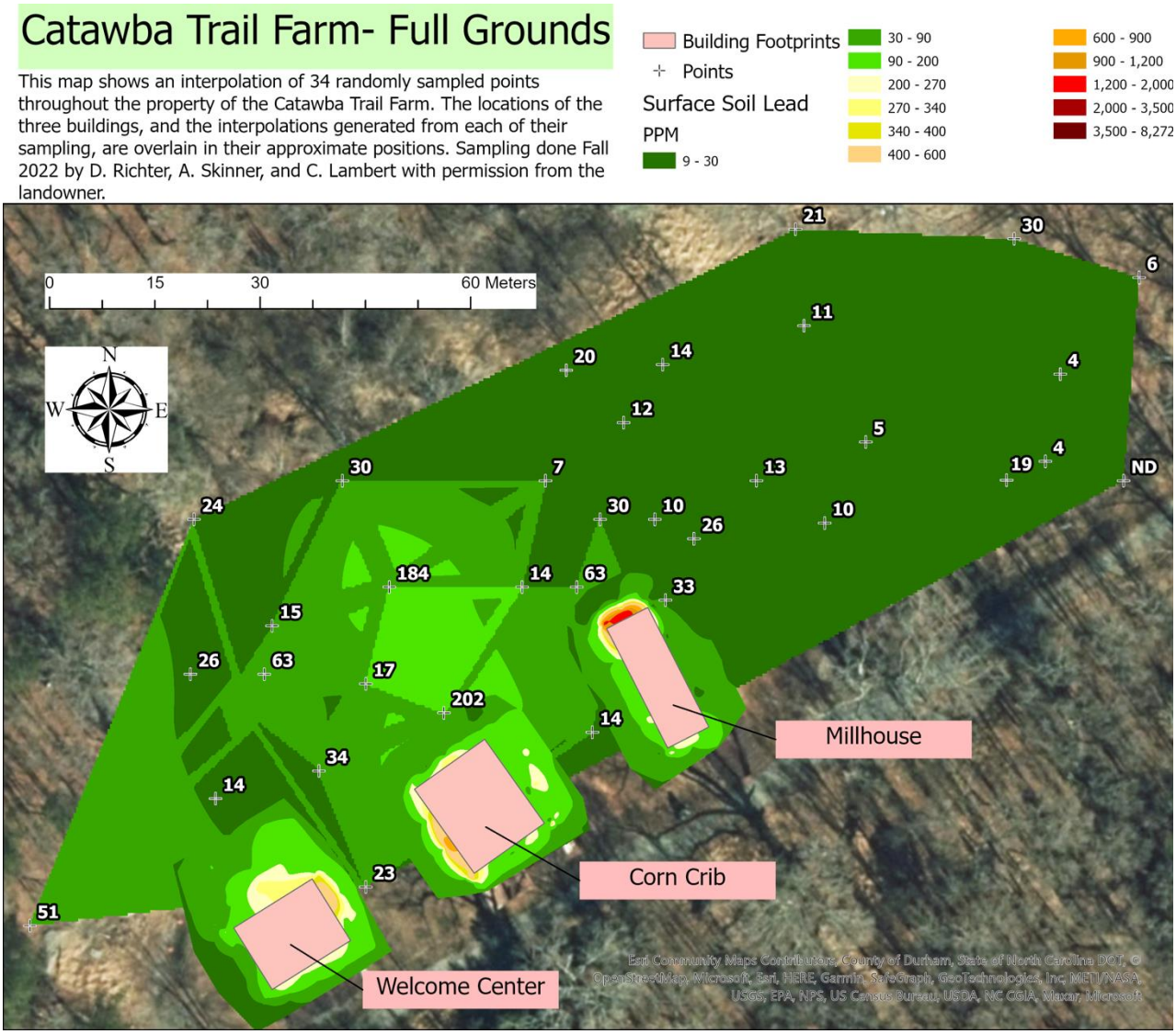

Figure 11. The full grounds of Catawba Trail Farm, including an interpolation from randomly selected points throughout the property. The locations of the three buildings and their interpolations are overlain.

Stagville Plantation- Hart Family House

A different sampling design at the Hart House gave us better sampling efficiency while still including four longer transects that allowed us to approach the geologic background. On the south side of the house, a dense gravel parking lot comes within 2-3 meters of the foundation, which made sampling difficult and led to some of our lowest measurements 2 meters from the house. None of these five samples exceeded 30 ppm. Aside from this, the spatial pattern is fairly consistent around the building, with most of the 0.5m points ranging between 100 and 250ppm. No clear directional patterns of contamination are present, nor are there any obvious hotspots. The maximum value, 275ppm, was recorded twice- once at the southwest corner and once on the east face. Overall, soil lead concentrations at this site are relatively low compared with the other historic structures in the study, but it important in that it shows consistent spatial patterns can be found regardless of maximum total concentrations.

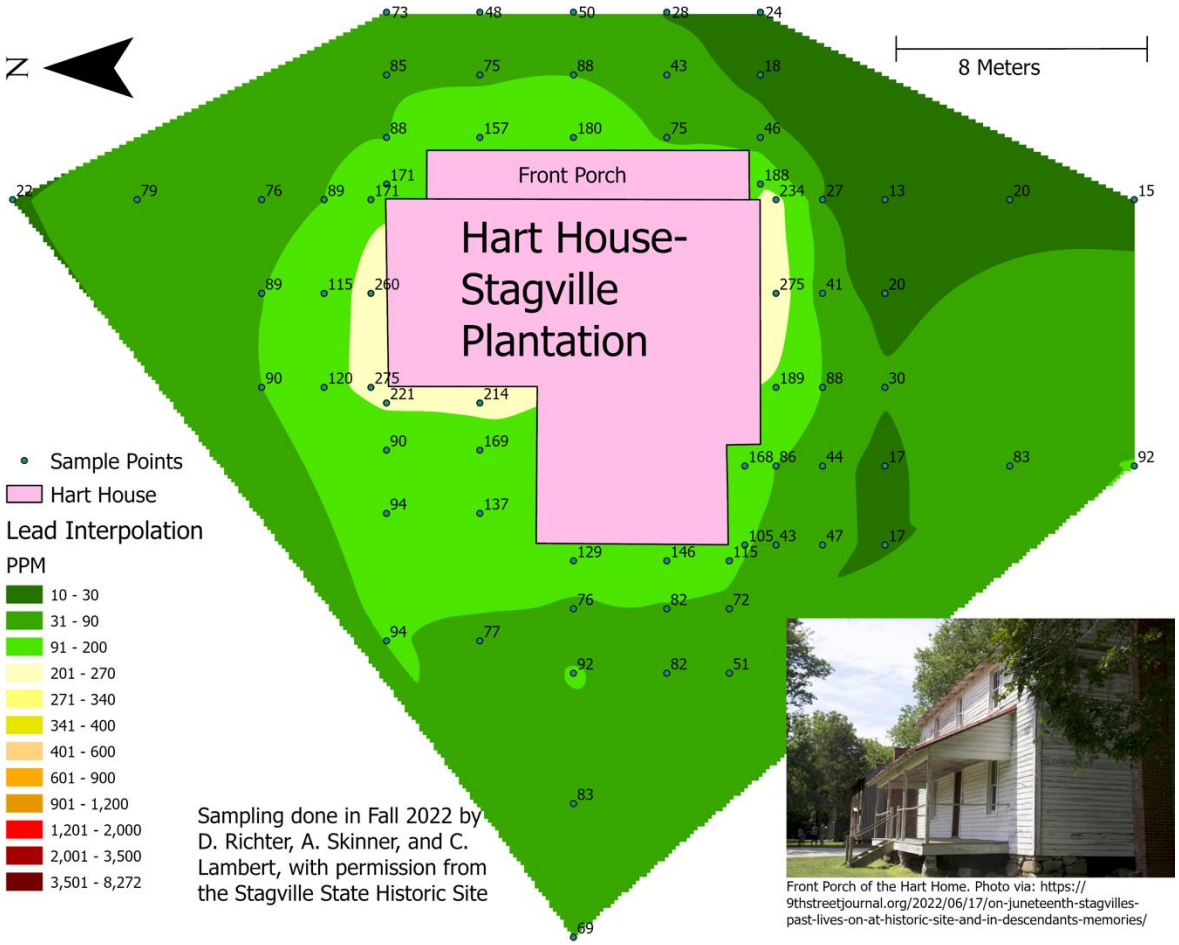

Figure 12. The home of the enslaved Hart Family at Stagville Plantation.

Nettie's House

This was our first of two structures that were completely collapsed. Our first challenge was to determine where the house actually stood prior to the year Nettie's house burned to the ground. This task was made especially difficult given the dense Wisteria vines that have captured the house site. Our sample design prioritized points inside the outline of the former foundation, because this provides us information we do not get from most of our other sites. The variety of bricks and building rubble made it difficult to find the upper surface of the mineral soil, which appeared to be mixed with the ash bed from the house fire. Despite to the passage of 30 years, Figure 13 clearly shows that the legacy of lead is still very strong, practically showing us where the house was without even needing to know! Unlike many structures where the lead is still on walls, or under newer coats of paint, the fire would have returned all of these materials to the soil, which could explain the extreme hotspots seen on points close to the walls. The two highest readings of any of our study sites were found here, just inside the north and south walls, towards the west end of the building: 8,692 and 11,440ppm (This latter value represents soil that is 1.1% lead!). Other high values are also found adjacent to former walls of this structure that had been painted on inside and out: including 4606ppm on the south face, 5232 on the east face, and 2889 on the west face. Around the exterior, the high concentrations are found fairly evenly on every

side, with values decreasing to 100-200ppm within 2-4 meters. Figure 14 shows an interesting spatial pattern within the house, in which the most interior points in the footprint have lower concentrations than those near the north and south walls.

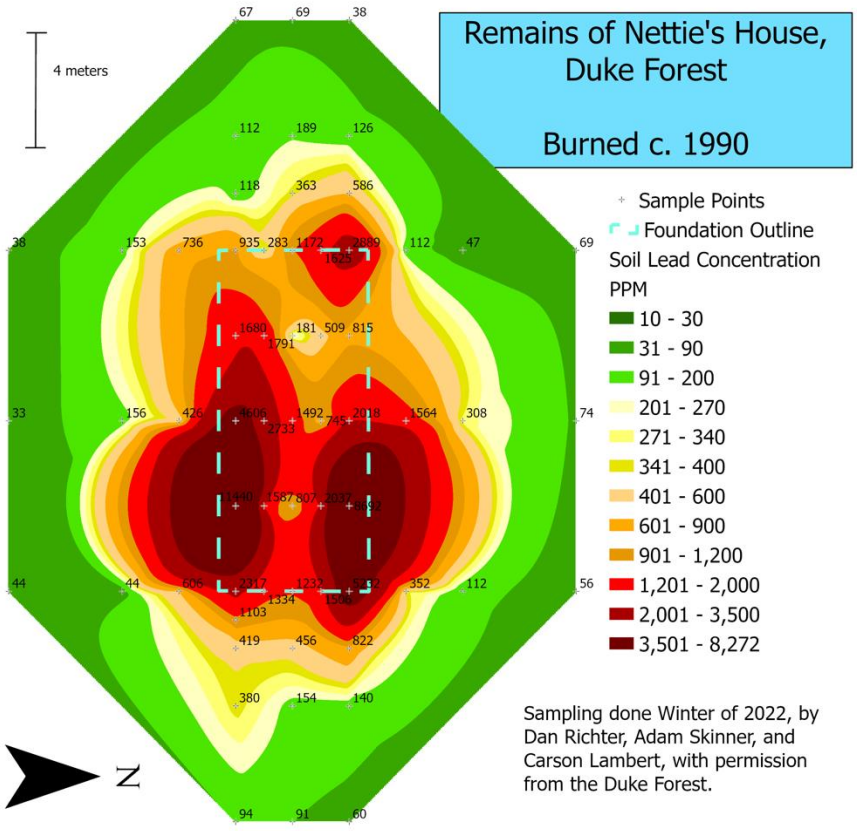

Figure 13. Soil lead concentrations at Nettie Couch's burned home in the Durham Dvision of the Duke Forest.

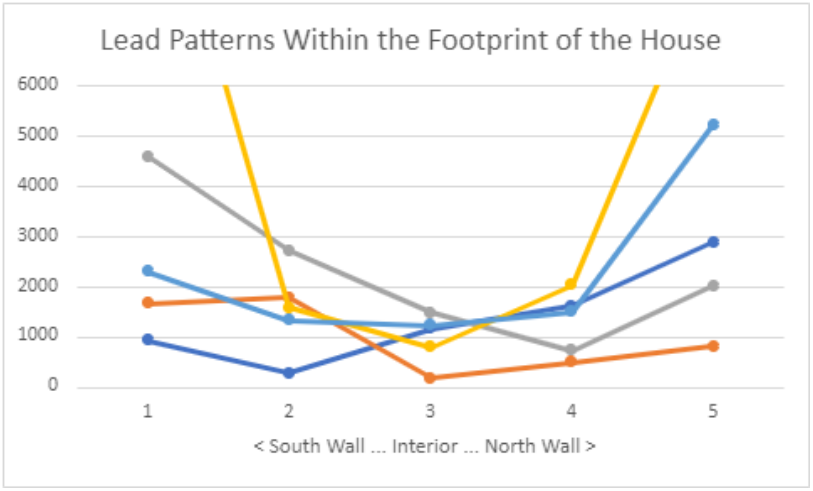

Figure 14. Each color represents 5 points along a south-to-north transect within the interior of the house. The figure shows that lead concentrations tend to be higher near the building's walls than they are at the house interior.

Eubanks Road Church

The church is a significantly larger structure than Nettie's house, allowing a larger sampling grid of points inside and outside of the structure. Unlike Nettie's house, however, soil lead concentrations were fairly low, with only five samples > 500ppm. Many samples ranged from 100-200 ppm, suggesting that the building had indeed been painted. In the interior of the building's footprint, three primary hotspots stand out. It is notable that these three sites all appear to be multiple square meters in area, with elevated reading outside just the 'center' of the hotspot that don't seem to be explained by the debris covering the ground. Unfortunately we will never know what characteristic of the church, or of the fire that destroyed it, deposited lead in such distinct hotspots. For the exterior transects, we surveyed out to 5 meters beyond the foundation, and found lead concentrations that decreased to geologic background levels on most transects, although a transect near the southwest corner had two high points, including a reading of 339ppm at four meters from the church.

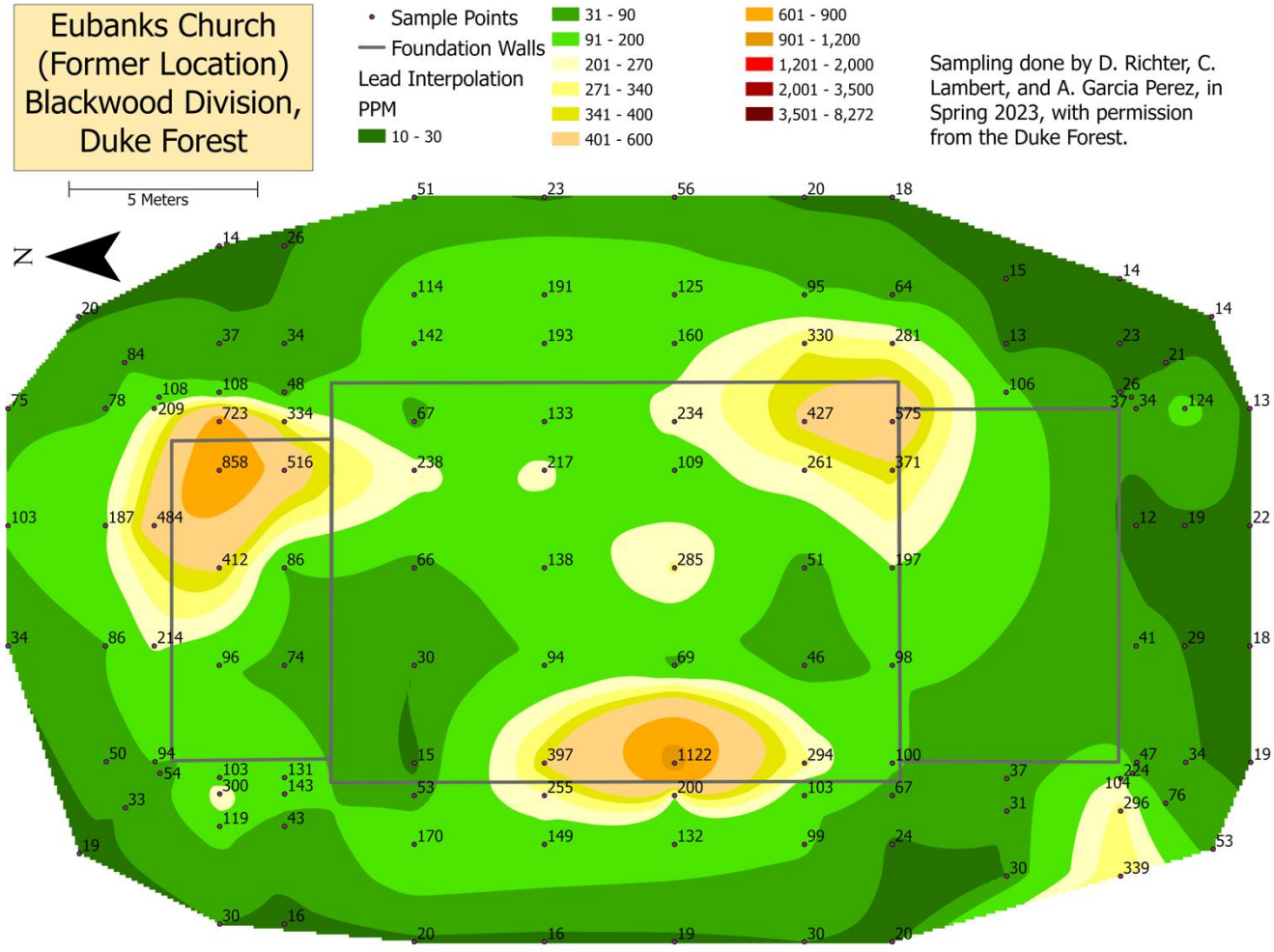

Figure 15. The Footprint of a burned and abandoned church in the Blackwood Division of Duke Forest, just north of the community of Eubanks.

Other Analytical Results

There are many factors that will affect the extent of soil lead contamination around buildings painted with lead paint. Unfortunately, very few will have detailed records of building upkeep, painting frequency, and soil and grounds management. Upon arriving at a site, we had little idea way of knowing whether it would end up in the moderate contamination or high contamination category, or even know for sure if it had been coated with lead paint. Understanding paint chemistry and usage among different kinds of historic structures is one way that we can better understand legacies of contamination. Paint chips flaking off of the buildings were collected at the Catawba Trail Farm corn crib and at the Stagville Plantation's Hart House. These chips were ground and sieved, and used to create pucks that can be analyzed by our XRF instrument. As Table 2 shows, different types of paint can contain dramatically different lead concentrations. An additional sample provided from an old family rocking chair owned by a lab member illustrates that lead can make up over 10% of a paint by composition. As higher quality paint typically used to contain higher concentrations of lead, socioeconomic factors may play a role in contamination risk. E.g., the Hart House was inhabited by an enslaved family that probably did not have access to the finest paints, and today shows much lower concentrations in the soil than the corn crib at Catawba Trail Farm (though this is purely speculative).

Table 2. Lead concentrations contained in paint chips from 3 sources (2 of our study sites). For the two study sites, the five maximum soil concentrations observed are also listed for comparison.

Paint Collection Site	Paint Chip Concentration	Highest Soil Concentrations (ppm)
Stagville- Hart House	714ppm	275, 275, 260, 234, 221
Catawba- Corn Crib	36,330ppm (3.63%)	758, 468, 444, 371, 362
Old Family Rocking Chair	101,500ppm (10.15%)	--

It is clear from the various maps that there is a strong inverse relationship between distance from a structure and the soil lead concentration, and statistical analysis helped quantify these patterns. Looking back to the Ark, Figure 16 shows boxplots of data at each measurement distance from the building. From the 0.5m distance to the 8m distance, the differences between the concentrations are stark- none of the average bars overlap with the interquartile ranges of their neighbors. Between the 0.5 and 2m distances, the interquartile ranges do not overlap at all. The only boxplots with significant overlap are between the 8 and 12m distances, where the concentrations begin to approach the geologic background. Figure 17 shows similar data generated from the Hart House. Because of the lower overall concentrations of the Hart House, the differences between boxplots are not as dramatic, as at the Ark.

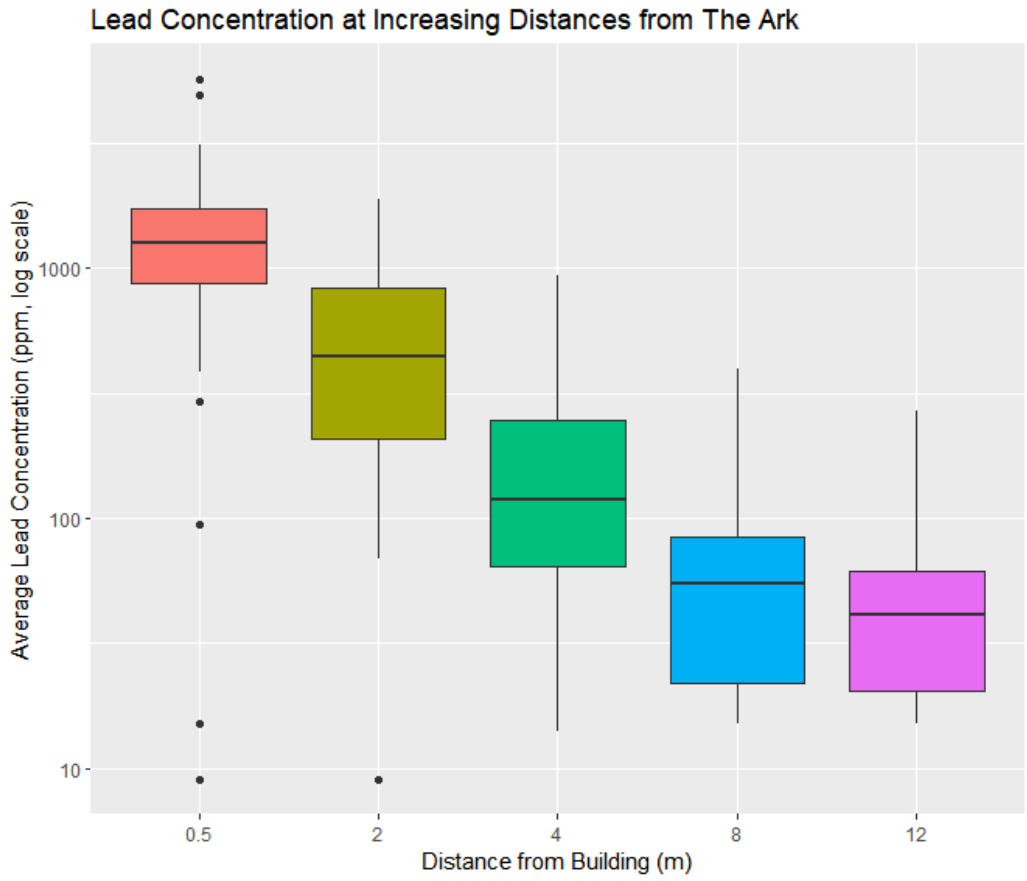

Figure 16. Average lead concentration by distance from the Ark. Each boxplot represents a composite of 28-31 points from the various transects. Note that the data is plotted on a log scale, actually masking the some of the true degree of variation.

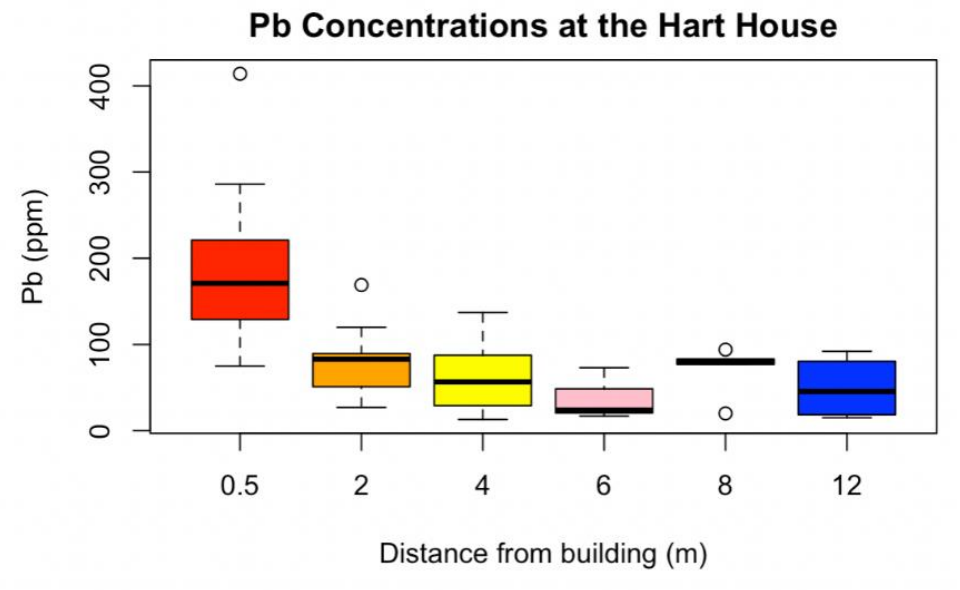

Figure 17. Average lead concentration at varying distances from the Hart House.

Instead of using a log scale, Figure 18 simply plots the means for each distance group on a normal scale. The mean at 0.5m was 1567ppm. However, at 2 meters distance concentrations on average are reduced by nearly 2/3rds to 585. This exceeds EPA's threshold concentration for soils in play areas. At 4 meters from the foundation, concentrations average 222ppm. Not as troubling as the previous numbers, but considering the "no safe level" principles for lead exposure, this is still a concerning contamination, especially so far from the actual walls of the structure. At 8 and 12 meters, the averages are 91 and 63 respectively. This approaches the geologic background level, but even at 12 meters this value suggest that the structure could still be influencing soil lead concentrations. Looking at the figure, it appears that a very smooth exponential or polynomial regression line could be generated from the points and explain a high percentage of the variance.

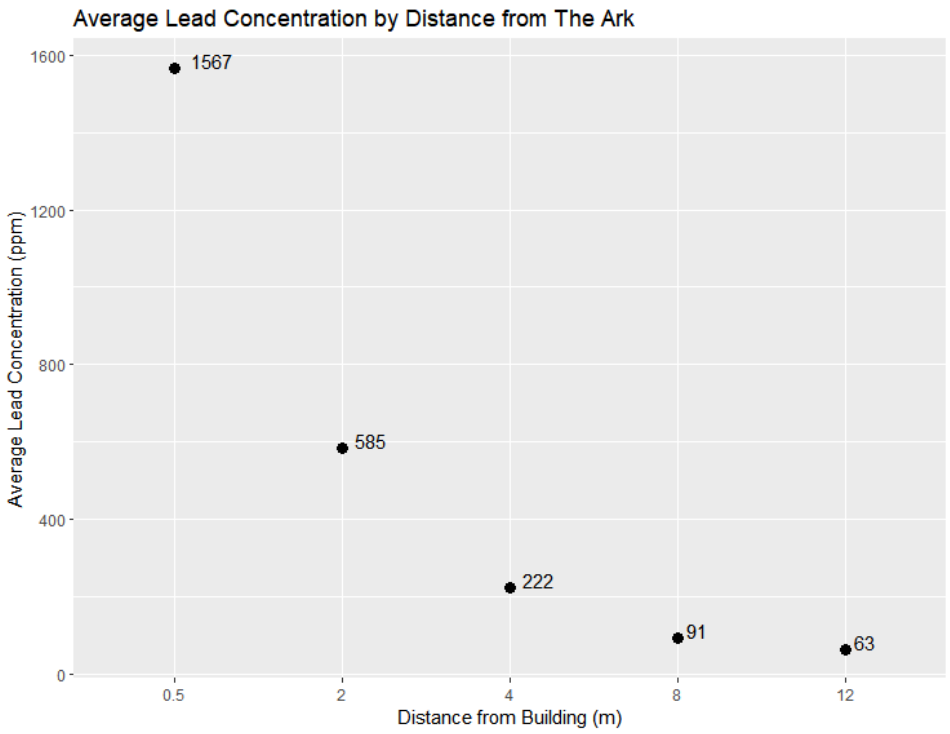

Figure 18. Averages of lead concentrations at increasing distances from The Ark.

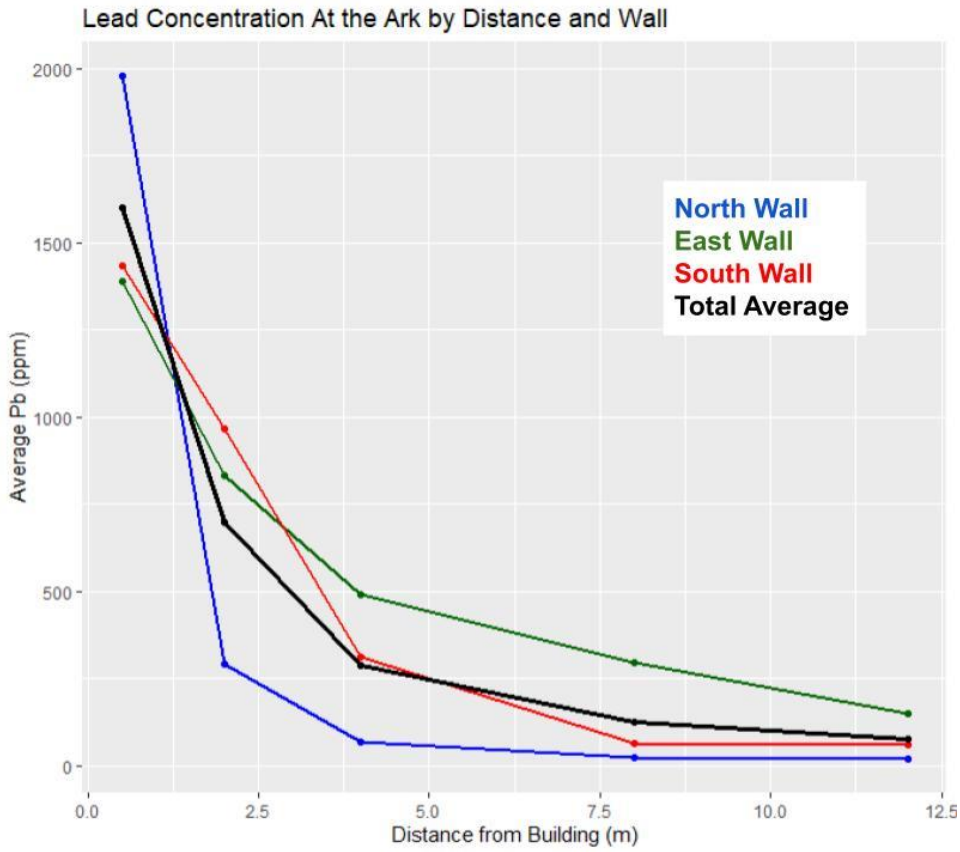

Figure 19. The same data as Figure 18, but broken up by the three walls that had regular sample spacing away from the structure.

Figure 18 is helpful in that it allows us to see generalized patterns in concentration as you move away from the wall, but as we have seen from our maps, there is spatial variation in hotspots that can't just be explained by distance from the structure. One way that we attempted to tease out this variation is by looking at data for three faces of The Ark individually (Figure 19). Although all three lines show a similar pattern of rapid decay with increasing distance, they have slightly different patterns. On the north face of the building, concentrations 0.5m from the building were over 25% higher than the averages from the east and south faces. However, at 2m, soils on the north average drops down to below 300ppm, while for the other two faces the average stays above 750ppm. The low values on the north side are likely attributable to recent construction work disturbing the soil.

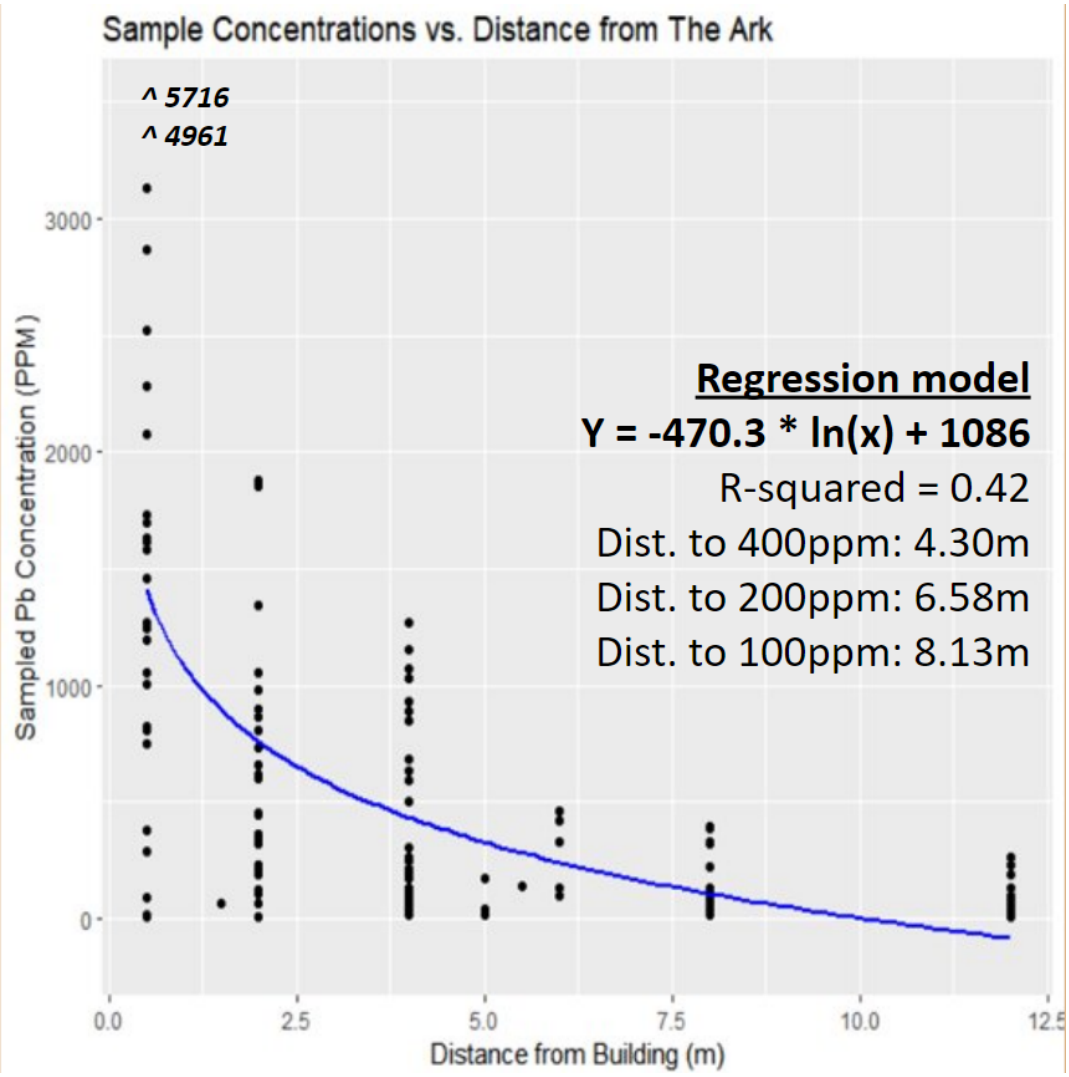

Figure 20. All 190 data points from The Ark versus their distance from foundation. A logarithmic regression is also shown for this data.

Compared to Figure 18, which only shows the averages at standard distances, Figure 20 shows all data. Although there is large variation at any particular distance, it is clear that the distance trend is real. A logarithmic regression was estimated for these data in R and the non-linear equation shown on the figure. According to the R-square, distance from The Ark explains 42% of the variation in lead concentrations. The rest of the variation will result from variation in paint weathering, soil erosion, and pedoturbation over 120 years since construction. For the Ark, this equation predicts a concentration above 400ppm within 4.3m of the structure, declining to 200ppm at 6.6m, and finally dropping below 100ppm beyond 8.1m.

Regressions like that in Figure 20 were estimated for all 9 of our structures (Table 3). For the burned structures, only data outside the footprint of the structure was used. These regressions varied in the amount of variance they captured, from a max of 0.5 at Nettie's House to a low of 0.18 at the Eubanks Church. Figure 21 shows this data as a graph, with a line for each structure showing the distance away from the structure you would have to travel to get lead concentrations to decline to each of the 3

thresholds. There are two main takeaways from this graph. First, there is a clear split between the high contamination sites and the moderate contaminations sites, with the moderate sites have generally no area above 400ppm. The second is that each structure, especially the high contamination sites, has its own pattern of decay over space. This is illustrated by the fact that the distance to 400ppm is nearly identical for Nettie's House and Broken Spoke Farm, but at Nettie's house you would have to travel almost twice as far to get down below 100ppm.

Table 3. Logarithmic regressions were generated for each structure, which were used to estimate the distance you would have to move away from each structure to get lead levels down to 400, 200, and 100ppm.

Structure	Log. Regression	R^2	Dist to 400ppm	Dist to 200ppm	Dist to 100ppm
The Ark	Y = -470.3*ln(x) + 1085.8	0.42	4.30	6.58	8.13
Stagville- Bennehan Home	Y = -314.9*ln(x) + 754.63	0.31	3.08	5.82	8.00
Nettie's House	Y = -362.1*ln(x) + 738.79	0.50	2.55	4.43	5.84
Broken Spoke Farm	Y = -1298*ln(x) + 1601.3	0.44	2.52	2.94	3.17
Catawba- Kitchen	Y = -127.2*ln(x) + 163.63	0.14	0.16	0.75	1.65
Catawba- Corn Crib	Y = -94.11*ln(x) + 156.9	0.31	0.08	0.63	1.83
Catawba- Welcome Center	Y = -62.68*ln(x) + 152.15	0.31	0.02	0.47	2.30
Stagville- Hart House	Y = -45.5*ln(x) + 136.08	0.53	0.00	0.25	2.21
Eubanks Church	Y = -40.69*ln(x) + 107.09	0.18	0.00	0.10	1.19

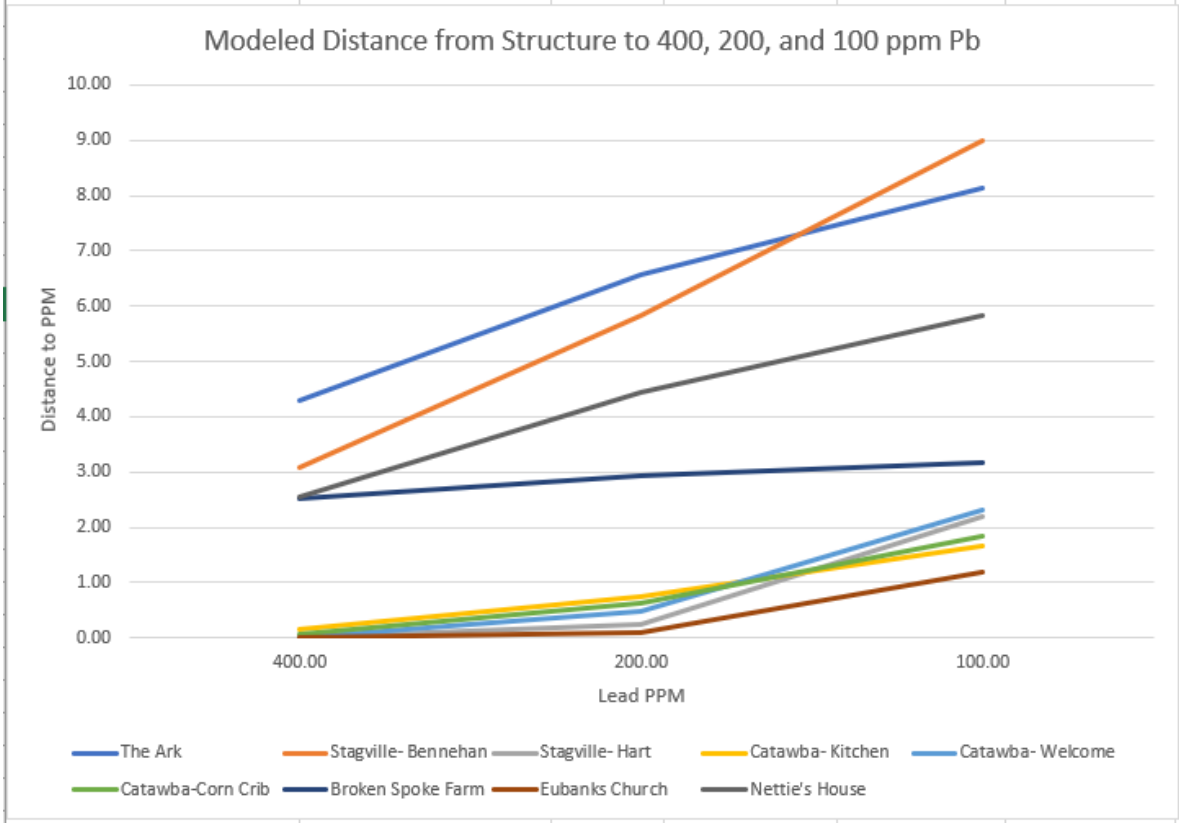

Figure 21. The distances/PPMs from the logarithmic regressions in table 3.

The spatial exploration also produced data that could be important for management and remediation purposes. Using the method of georeferencing the interpolation and calculating area, the area of contaminated soil was found for the Stagville- Bennehan house (Table 4) and The Ark (Table 5). At the

Bennehan house, over 66% of the area we surveyed had lead elevated above 200ppm. About half of this area was above 400ppm, or a third of the total study site. 32.6% of the study area was above the general threshold of 400ppm- 152 square meters of contaminated soil is not insignificant, especially as this is a historic site open to public education and is frequently visited by children. At The Ark, our study area was much larger in size, due to the larger building size and the measurements out to 12 meters. Despite this, we still observe over half of the area being above 200ppm, and over 30% being above 400 ppm. This equates to an area of almost 430 square meters of ground with lead levels above this EPA threshold. The Ark formerly hosted the first basketball court used by the Duke Blue Devils, and now hosts an area of toxic soils larger than a basketball court (429.6 vs 420m^2)! Of that area, nearly 120 square meters breech the 1200ppm threshold.

Table 4. Results from the spatial exploration of the Stagville Plantation- Bennehan house.

Estimated Area of Soil Lead contamination- Stagville Plantation Home		
	Area (m2)	**% of study area**
Total Area	467.0	100
>200 ppm	308.6	66.1
>400 ppm	152.0	32.6
>1200 ppm	17.3	3.7

Table 5. Results from the spatial exploration of The Ark.

Estimated Area of Soil Lead contamination- The Ark		
	Area (m2)	**% of study area**
Total Area	1417.4	100
>200 ppm	721.8	50.9
>400 ppm	429.6	30.3
>1200 ppm	119.3	8.4

Estimating the total area in the study site for these structures also allowed us to estimate our sampling density by dividing the total area of the georeferenced interpolation by the number of sample points at each site. Since our spacing between points generally increases further away from the building, the overall point density will be lower at sites where we sampled at a greater distance from the building. At the Bennehan house, total area interpolated from our points was 467 square meters of soil, and we had 111 total sample points. This represents a sample density of 0.23 points per square meter, or one point every 4.21 square meters. At The Ark, the total area was much larger because our transects extended out 12 meters (vs. 7 meters at the Bennehan house): 1417.4 square meters. This was also our most intensive sampling location, with 185 points. This is a sampling density of one point per 7.66 square meters, or 0.13 points per square meter.

Discussion

We found a great deal of spatial variation in lead concentrations through this study, both within and between study sites. For example, the Bennehan house and the Hart house, both part of the historic Stagville plantation, have maximum hotspot values ranging over an order of magnitude. There are two primary theories for why this could be the case: Either the initial lead paint applications varied in lead concentration or amount of paint used, or the frequency/methods of painting has affected how much lead has been released to the soil. The Hart House appears to have been painted less frequently than the Bennehan house, which is the centerpiece of this historic site. Perhaps this means that the lead began flaking off very quickly and has not persisted on the side of the house, with soil levels returning to lower values over time as sediment is eroded and transported away. Alternatively, it is possible that because the Hart house was occupied by an enslaved family, it was not painted as often, or with as high-quality paint (meaning higher lead levels). Thus, the total lead inputs to the surrounding soils may be lower, explaining the lower soil values.

From what we know about our sites, it is difficult to predict what kind of structures are likely to show high lead concentrations. Both of our well-maintained sites had high levels, but this is a limited sample size. Only one of the five dilapidated sites had high concentrations, as did one of the two destroyed sites. No clear patterns can be seen between building types or surrounding landscapes. However, there are patterns within the maps that appear to hold true between multiple sites. Concentration hotspots are typically found close to the building, or close to the former walls of the building, and at some sites the corners of the building show the highest concentrations. Along a given transect away from a building, lead concentrations tend to decrease fairly rapidly until they reach the geologic background. Lead concentrations are often spread fairly evenly around the exterior of a building, rather than showing a clear directional pattern. Topographic variability can affect movement of lead, as soil and paint particles may be eroded downhill with water.

At the nine buildings surveyed, risk for human interaction with the soil varies widely. Soil lead risk can be described as a vector of toxicity and exposure. Catawba Trail Farm and Broken Spoke Farm both have programs bringing large number of children to their properties, who may well be playing in the soil around the structures, elevating the potential for exposure. The toxicity risk at Broken Spoke farm is high, as previously discussed, making the total risk high. At Catawba, the toxicity is significantly lower, creating only a moderate risk from soil lead. At Nettie's house, even though this is the site with the highest concentrations, the total risk is fairly low, because of the overgrown and remote nature of this site on Duke Forest, a controlled-access property. Any environmental effects of the lead contamination at these locations was not obvious during our site visits, but would be an interesting avenue for future study.

Table 5. The seven properties surveyed, ranked by total risk, which is a sum of the lead toxicity levels present and the opportunity for public exposure.

Site	Lead Concentration	Exposure Potential	Est. Health Risk
Broken Spoke Farm	High	High	**High**
Stagville- Bennehan home	High	High	**High**
The Ark	High	Moderate	**High**
Catawba Trail Farm	Low	High	**Moderate**
Stagville- Hart house	Low	moderate	**Low**
Nettie's House	High	Very Low	**Low**
Eubanks Church	Low	Very Low	**Very Low**

In thinking about risk and exposure more broadly, our fine scale resolution study illustrates the potential for dangerous exposure to lead soils for people living in historic homes. In the 1950's and 1960's, the onset of white flight from historic city centers to newer suburban housing stock coupled with racist housing practices contributed to disproportionate environmental risks for low-income black and brown communities. Some of these practices that inhibited community empowerment through financial means like redlining were explicitly racist—denying loans to minority communities despite otherwise being eligible. Some of the practices were more subtly racist such as the predatory FHA-backed sales of dilapidated homes in historic urban neighborhoods to low-income African Americans (Taylor 2019). Explicit or not, state sanctioned segregation has contributed to and resulted in unequal access to safe housing.

With this racist history of state sanctioned segregation resulting in affluent white people having access to newer and safer housing and low income and minority communities having access to older and less safe housing, it is unsurprising that there are disproportionate environmental consequences linked to this racist housing history. Disproportionate lead exposure is one of the consequences, with children and African Americans in low-income areas living in older homes having a greater risk of lead poisoning compared to white people (CDC, 2021).

This study is unusual in its production of fine-scale geospatial soil chemical mapping. This has been made possible thanks to relatively recent advancements in portable X-ray fluorescence technology that allows soil metal concentrations to be measured quickly and conveniently. With our sampling design, we have captured spatial variation at a fine scale not found in most previous studies of soil lead distribution. This allows us to better understand the spatial extent of hotspots and contaminant plumes, and helps in the characterization of total risk. This method also opens up other avenues of study, such as a deeper dive into how the history and upkeep of a building affect patterns of lead contamination. Other potential deep-dives could look at how topography and soil structure affect movement and retention of lead over time, or how the presence of lead affects biological communities in the soil.

Of course, soil lead contamination is a problem that extends far beyond Durham and Orange Counties. There are likely millions of buildings across the United States that were painted with leaded paint before the 1970s, and likely have similarly high lead concentrations in their soils. These sites surely include homes, schools, farms, hospitals, parks, and other public facilities where there is a high potential for people, especially children, to be interacting with the soil. Having a better understanding of the fine-

scale patterns and concentration gradients seen around these structures can better inform soil management and remediation decisions, and help protect people from harm.

Acknowledgments

This project would not have been possible without the many great collaborators who contributed their time, knowledge, and access to study sites. Our advisor Dr. Daniel Richter was an enthusiastic leader and helped us at every step of the way with his deep knowledge of soils and love of getting out in the field. Anna Wade and Enikoe Bihari completed soil lead projects that helped to inspire this one. Alberto Garcia Perez was a huge help during the Spring semester as he contributed to field work and research, while working on a complementary independent study of lead at soil depths. Many professors and staff at the Nicholas School provided guidance and insight, including Peter Harrell, Dr. Dean Urban, Dr. Joel Meyer, and others. We also owe a huge gratitude to the land owners and managers who allowed us to sample their properties, including Tom Craven and Sarah Childs at Duke Forest, Duke Facilities, Stagville State Historic Site, Broken Spoke Farm, and Delphine Sellars at Catawba Trail Farm.

The land where we studied and worked was originally territory of Tutelo and Saponi-speaking peoples, whose land was stolen by European colonization. Durham and Orange Counties continue to be home to multiple Native American nations, including descendants of Tutelo and Saponi peoples. Additionally, some of our study structures were on the property of a plantation that enslaved African Americans, and we wish to acknowledge the harm caused by the Bennehan and Cameron families at this site.

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