Summer 8-13-2021

Investigation of Environmental Lead Exposures in Children at A Midwestern City with Superfund Site

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INVESTIGATION OF ENVIRONMENTAL LEAD EXPOSURES IN CHILDREN AT A MIDWESTERN CITY WITH A SUPERFUND SITE

by

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A DISSERTATION

Presented to the Faculty of

the University of Nebraska Graduate College

in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy

Environmental Health, Occupational Health & Toxicology

Graduate Program

Under the Supervision of Associate Professor Chandran Achutan

University of Nebraska Medical Center

Omaha, Nebraska

August 2021

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ACKNOWLEDGEMENTS

The journey of earning a doctoral degree and completing this dissertation is long and challenging, and it is certainly not accomplished single-handedly.

First and foremost, I would like to express my sincere thanks to my academic advisor, Dr. Chandran Achutan, for all his invaluable guidance and advice throughout my entire Ph.D. career and this dissertation. Dr. Achutan, thank you for always being there for me academically and personally. Without your constant support, understanding, and encouragement, I would not have achieved what I achieved in my Ph.D. career or become an independent scientific researcher.

I would also extend my sincere appreciation to all my supervisory committee members for their expertise and guidance: Dr. Eleanor Rogan, Dr. Lynette Smith, and Dr. Dejun Su. I would like to thank Dr. Rogan for her support and encouragement throughout my doctoral education. Dr. Rogan, thank you for your great commitment towards the development and success of the students at the Department of Environmental, Agricultural, and Occupational Health. I would like to thank Dr. Smith for her constructive feedback and indispensable support during my dissertation. Dr. Smith, thank you for helping me overcome my weakness. Your feedback and guidance were irreplaceable throughout my dissertation writing process. I would like to thank Dr. Su for his expertise and overall support. Dr. Su, thank you for your advice and encouragement. They were influential on my doctoral program. I would also like to thank the faculty and staff at the College of Public Health, especially Dr. Lorena Baccaglini, Dr. Aaron Yoder, and Ms. Rachel Maley. This research was partially supported by the College of Public Health Innovation Fund. I am forever grateful for the knowledge I learned, the support I received, and the experience I got from this great college.

I am grateful to all my friends who have supported and helped me during this incredible journey, with special recognition to Alexandra Farfalla, Kaeli Samson, Troy Suwondo, and Caitlin Ray, it would not have been possible for me to complete my dissertation without your help. I would like to thank Austin Abelarde, Lindsay Abelarde, and Nathan Rowland for their greatest friendship and support. Special thanks to Libin Fan; thank you for your unconditional support and understanding. I sincerely wish you a rewarding and successful Ph.D. career ahead.

Last but certainly not the least. With my deepest gratitude, I thank my family for their love and support. Specifically, to my parents: Yanqing Liao and Yue Qin, thank you for giving me this life and your endless support for each and every day of my life. All I can say is thank you, and I love you dearly.

ABSTRACT

INVESTIGATION OF ENVIRONMENTAL LEAD EXPOSURES IN CHILDREN AT A MIDWESTERN CITY WITH A SUPERFUND SITE

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Childhood exposure to lead is known to cause a host of adverse health effects in children, with no safe blood lead level indicated. Environmental lead contamination is prevalent throughout the United States and remains a threat to the healthy development of children living in these areas, including children in Omaha, Nebraska. The overall objectives of this dissertation were to characterize potential sources of lead in the community – where children play and where children live through the use of environmental exposure sampling. This dissertation also provides insight into current Nebraska children's blood lead levels and identifies local populational attributes that may predispose children to lead exposure and subsequent adverse health outcomes.

The first study quantified soil and air concentrations of lead in Omaha, Nebraska parks. Home to one of the largest historically known lead-contaminated Superfund sites, local metro parks were examined both within the historically designated Superfund program area and outside of this area (n=60) using the EPA's soil sampling protocol. The geometric mean and median soil lead concentrations among 30 Omaha Lead Superfund site's parks were 28.3 parts per million (ppm) and 33.1 ppm, respectively. These two statistics were significantly higher than those in non-Superfund site parks (geometric mean=12.8, median=14.0, $p<0.05$). All air samples were with lead concentrations lower than the limit of detection.

The second study assessed residential indoor lead dust concentrations in Omaha and determine the potential determinants of elevated indoor lead dust concentrations. Data with windowsill and floor lead dust concentrations from 350 eligible households was analyzed. Our findings reaffirmed the existing indoor lead exposure issue in Omaha, as approximately one-third of participated homes had either windowsill or flood lead dust concentrations that failed to meet the EPA standards. Elevated indoor lead dust concentrations were more common among African American families (adjusted odds ratio [OR] =2.22; 95%CI: 1.18, 4.18) and the families that adults without any health insurance coverage (adjusted OR=1.90; 95%CI: 1.04, 3.46). Additionally, homes built before 1950 (adjusted OR=6.21; 95%CI: 2.32, 16.63) and inside the Omaha Lead Superfund site with a soil lead level exceeded 400 ppm (adjusted OR=2.45; 95%CI: 1.16, 5.18) had higher odds of having elevated indoor lead dust concentration.

The final study evaluated children's blood lead levels in the Greater Omaha area and the other areas in Nebraska by using electronic health records. Indication of elevated BLL (≥5 μg/dL) was used to quantify the prevalence of children with elevated blood lead levels in both areas. Findings indicated the incidence of elevated blood lead levels has decreased from 25% in the early 1990s to approximately 3%, among children living in the Greater Omaha area. However, the statistics suggested childhood lead poisoning may still be a public health problem in Omaha, NE, as the incidence of elevated childhood blood lead was higher than the national surveillance level. Only a few children's blood lead tests (<2%) were conducted because there was suspected exposure to lead. This finding suggests the need for future research to determine children's environmental lead exposure and elevated BLL.

Collectively, these studies sought to identify current and historical sources of lead exposures among children and the adverse effect childhood lead exposures can have on

their healthy development. Using environmental exposure sampling and electronic health records data on BLLs of children, we provide evidence that lead exposures may be declining, but the burden of lead exposure on a child's health remains prevalent in Omaha, NE. The highlight of this dissertation is that elevated indoor lead dust concentration is prevalent in Omaha, NE, especially for those who with certain lower socioeconomic status. These findings are evidence of environmental justice issues and health disparities in childhood lead exposure in Omaha, NE. Therefore, we recommended several plans of future lead related research, policy making, and management plans in Omaha, NE. With collaborative efforts through partnerships between health departments, academic researchers, and community members, we hope to reduce and eliminate lead exposure so that a better living environmental can be provided to our children and community.

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CHAPTER 1: INTRODUCTION

Protecting children from lead exposure is essential to lifelong good health. The current children's blood lead reference value of five μg/dL adopted by U.S. Centers for Diseases Prevention and Control (CDC) is stringent (Centers for Diseases Prevention and Control [CDC], 2012). However, there is no safe blood lead level in children. Even low levels of lead can adversely affect multiple body systems and development. Furthermore, once lead enters the body and accumulates enough to present symptoms, no effective treatment can correct them. There are still many locations throughout the U.S. with significant numbers of children with lead exposure, including Omaha, Nebraska, where lead contamination has been a longstanding public health concern. The overall objectives of this dissertation were to characterize potential sources of lead in the community, evaluate current residents' blood lead levels, and seek methods to identify future lead poisoning prevention and management better. To accomplish these objectives, three independent studies were conducted:

1) Quantify the lead levels in Omaha public parks' soils and assess potential contributors of soil lead contamination.

2) Assess the residential indoor lead dust concentrations in Omaha and determine the potential determinants of elevated indoor lead dust concentrations.

3) Evaluate and review Omaha children's blood lead level by using electronic health records and assess the clinical reasons for children receiving blood lead tests.

Organization of the dissertation

The dissertation is organized as follows:

Part I describes the background of this research, including research objectives, background information on lead, previous research on lead exposure and poisoning, and current challenges. Part II includes the three independent studies of this research project. Finally, Part III presents the conclusions and plans for future research.

In Part I, Chapter 1 introduces the motivation and need for this research project, along with the organization of the dissertation. Chapter 2 presents a brief literature review and introduction of lead, lead toxicity, lead in environmental media and related regulations, childhood lead poisoning and blood lead levels, and historical and current information on the Omaha Lead Superfund site.

In Part II, we present methods and findings from three independent studies. Each chapter contains one independent study.

Chapter 3 mainly presents the findings on soil lead levels in Omaha public parks from one preliminary study and one full-scale study. We also present air lead concentrations and findings on geospatial and atmospheric determinants of soil lead concentrations. There are three research questions in Chapter 3: 1) What are the soil and air lead concentrations in Omaha public parks? 2) Are there significant differences between soil lead concentrations in Omaha public parks inside the Omaha Lead Superfund site compared to the parks outside? 3) What are the potential determinants of higher soil or air lead concentrations?

Chapter 4 focuses on assessing residential indoor lead dust concentration and potential determinants of elevated indoor lead dust concentration. There are two research questions in Chapter 4: 1) Do homes inside the Omaha Lead Superfund site have a significantly higher average and median concentrations for both indoor floor and windowsill lead dust compared to the homes outside? 2) Which home and resident characteristics are associated with an indoor lead dust concentration that exceed the U.S. Environmental Protection Agency (EPA) standards?

Chapter 5 presents findings on hospital visited or admitted children's blood lead levels. There are two research questions in Chapter 5: 1) What is the prevalence of elevated BLL among hospital visited or admitted children who had blood lead tests? 2) What are the main clinical reasons that children had blood lead tests?

In Part III, Chapter 6 answers the research questions posted in Part II and describes our sense of this dissertation's significance. Finally, we outline the potential directions of future lead research in Omaha.

CHAPTER 2: LITERATURE REVIEW

Upon finding lead toxicity as one of the most common diseases of toxic environmental origin, perception of lead has changed significantly. Historically, lead was considered one of the most useful metals that laid the foundations of empires and promoted the development of human societies. Countries have different degrees of understanding and recognition of lead poisoning problems due to historical, industrial, and economic reasons. Like the U.S., which used to be the leading country of lead production and usage, some countries now have established regulations and standards to ban certain uses of lead and remove lead hazards from living and working environments. Since the 1990s, environmental lead contamination and human blood lead concentrations in the U.S. have declined dramatically. However, the occurrences of childhood lead poisoning in several locations across the U.S. (Handley, et al., 2007; Butler, et al., 2016) indicated that lead exposure is still a national public health problem. Omaha, Nebraska, is one of the significant lead-contaminated locations in the U.S. where childhood lead poisoning is a public health concern. Examination and treatment of lead contamination in Omaha has improved the health of the environment and the public. However, there is always room to improve, and work needs to be done. By conducting this research, we hope to address the importance of providing up-to-date lead poisoning information to our residents and thus apply evidence-based prevention strategies in our community.

Lead and Toxicology of Lead

History of lead production and usage

Lead is a dense, soft, and low-melting metal naturally occurring and found in the earth’s crust (Acharya, 2013; Agency for Toxic Substances and Disease Registry [ATSDR], 2021). Lead only makes up about 0.0013 percent of the earth’s crust, but it is not considered rare (ATSDR, 2021). There are more than 60 minerals widespread in the world containing lead, and it is easy to extract lead from its ores.

Lead was one of the first metals known to and used by humans, with the earliest knowledge of lead tracing back to 6,400 BC (Acharya, 2013; Hernberg, 2000). Lead was commonly used for pewter and tableware throughout the Antiquity as it was suitable for casting. Due to its malleability and ability to resist water corrosion, lead was frequently used in building the Roman Empire's water pipes (Hernberg, 2000; Acharya, 2013). The use of lead expanded to industrial, domestic, and medicinal areas during the Middle Ages. Lead was primarily used in roofing and shipbuilding because of its corrosion resistance attribute (Hernberg, 2000). Lead was also used as a sweetener and added to wine and ciders (Hernberg, 2000; Riva, et al., 2012). Between 16th and 17th century Europe, lead was commonly used in cosmetics to obtain a "white-faced" look that was considered popular and elegant (Pedersen, 2016).

Since the Industrial Revolution, the production and usage of lead have significantly increased, as people called it "the useful metal." Lead was considered adaptable to any commercial purpose and therefore was widely used in ammunition, crystal glass, gasoline, lead-acid storage batteries, paint, and pigments (Hernberg, 2000; Riva et al., 2012). Lead may have entered the environment from the wide variety of lead products' uses. However, it was the industrial production of lead that contributed to the significant lead emissions and pollution. For example, the U.S. was the leader of lead production and usage in the world from 1900 to the mid-1970s (Lewis, 1985; Rich, 1994). The highest output of lead production and record usage was 0.63 million tons and 1.50 million tons in one year, respectively (United States Geological Survey [USGS], 1990). Most of the U.S. lead mining, smelting, and refining facilities were located in the west north central (e.g., Missouri and Nebraska) and mountain regions (e.g., Colorado, Idaho, and Utah) (USGS, 2021). The environmental lead levels have substantially increased around these industrial lead production facilities, leading to an epidemic of lead poisoning that caused adverse health effects among the public.

Lead Toxicity

Lead exposure has been a public health concern in human history, with the earliest records of lead poisoning found about 2,500 years ago (Hernberg, 2000). However, the toxicity, mechanisms, and health impacts of lead poisoning were not fully recognized until the 1960s and 1970s (Hernberg, 2000; Parsons and McIntosh, 2010; Mielke, et al., 2019).

The earliest acknowledgments of lead toxicity can be found in Egyptian papyrus scrolls, which suggested lead compounds were used for homicidal purposes (Hernberg, 2000). Hippocrates in 370 BC and Hellenistic physician Nicander of Colophon in the 2nd century BC both described colic and palsy related to lead exposure (Hernberg, 2000). However, both of them were not able to attribute the adverse health symptoms to lead exposure, and thus the etiology of lead poisoning was not recognized (Hernberg, 2000).

From the late Antiquity to the pre-industrial period, physicians and researchers consistently recognized both lead poisoning and its connection to occupational lead exposure. The notable findings included Paracelsus' finding of the miner's disease in 1534 (Borzelleca, et al., 2000), and Ramazzini found potters who worked with lead became paralytic, splenetic, lethargic, cachectic, and toothless in 1713 (Ramazzini, 1713; Hernberg, 2000). Additionally, findings from the outbreaks of lead colic in Europe advanced the understanding of lead poisoning. A German physician, Eberhard Gockel, firstly traced a colic epidemic to lead-adulterated wine in 1696 (Eisinger, 1982; Riva et al., 2012). In 1767, Sir George Baker identified that the Devonshire colic (Baker, 1768), a condition which began with severe abdominal pains and occasionally led to fatal consequence, was associated with the lead-contaminated cider (Chisolm Jr., 1971; Hernberg, 2000). Therefore, the etiology of the colic was then confirmed as lead poisoning. However, there was still a lack of understanding of lead poisoning and evidence of lead poisoning clinical symptoms and description in the literature.

Knowledge of lead toxicity and its health impacts have significantly increased since the 19th century. Massive lead production and usage since the Industrial Revolution became important causes of morbidity and mortality among the general population (Hernberg, 2000). The earliest known effects of lead toxicity included lead colic, palsy, and encephalopathy (Hernberg, 2000). Through the epidemic of lead poisoning, physicians and researchers continuously recognized the adverse health symptoms related to lead exposure. These health symptoms and issues included but were not limited to: anemia, joint and muscle pain, hypertension, adverse renal function, neurodevelopmental disorders, reproductive system diseases, and carcinogenicity (Hernberg, 2000; Needleman, 1999).

Lead can enter the human body by three major pathways: direct ingestion through the gastrointestinal tract, inhalation through the respiratory tract, and dermal absorption through the skin (Markowitz, 2000; Papanikolaou et al., 2005). For adults who work with occupational lead exposures, the most significant route for lead absorption is inhalation through the respiratory tract (Philip and Gerson, 1994; Papanikolaou et al., 2005); whereas for children, the predominant absorption route is through direct ingestion (Papanikolaou et al., 2005). Following the exposure to lead, the element is absorbed into the bloodstream and then transported to tissues and organs. Blood, soft tissues, and bones are the three major compartments for lead accumulation in the human body. The biological half-life of lead in an adult’s body varies by those three compartments: about 35 days in blood, 40 days in soft tissues, and 20 to 30 years in bones (Rabinowitz et al., 1976; Roberts et al., 2001; Papanikolaou et al., 2005). Research indicated that the half-life of lead could be longer in children's bodies than in adults. In addition to the long biological half-life, lead excretion is extremely slow in the human body, with urinary tract and biliary clearance being the most significant excretion routes (Philip and Gerson, 1994). Therefore, exposure to lead and its subsequent absorption can accumulate in the human body.

Because lead is quickly absorbed into the bloodstream, blood lead level (BLL) has been used as the primary indicator of lead toxicity. During the mid-20th century, a BLL of 80 micrograms per deciliter (μg/dL) or higher was believed to result in lead poisoning. Additionally, there was no defined BLL standard or recommendation until 1971 (Graef et al., 1971). Since the 1970s, advanced understanding and knowledge of lead toxicity has led to stringent regulations on BLL. The definitions, criteria, and regulatory values of BLL have been scientifically revised and improved in the U.S. Furthermore, strict regulations and effective preventions applied in occupational and environmental settings substantially decreased the lead contamination in the U.S., and thus clinically symptomatic lead poisoning cases during the same period also declined significantly. From occupational health to environmental health; lead research and prevention has shifted from the clinical outcomes of high-dose lead poisoning among working adults to the consequences of a lower level of lead exposure that could potentially be asymptomatic among children.

Lead in the environment

Environmental lead contamination and exposure risk have been a public health issue in the U.S. and globally. Major sources of environmental lead in the U.S. include lead emissions from industrial activities, legacy sources that contain lead as an additive, and the usage of lead-contaminated consumer products (Harrison, 1981; Ab Latif Wani, 2015).

Because lead causes significant public health problems in the U.S., multiple federal agencies coordinated by the U.S. Environmental Protection Agency (EPA) have been committed to regulatory management of environmental lead contamination and exposure. A number of advisory standards or enforceable regulations that set lead levels in different media have been issued since the 1970s.

Lead in soil

Lead-contaminated soil is an important hazardous source of lead exposure for humans, especially for young children. The primary contamination sources of soil lead in the U.S. are anthropogenic. These anthropogenic sources can be historical and contemporary. Historic lead mine and smelters communities possess the greatest lead poisoning risk to children. Primary industrial production of lead from mining, smelting, and refining contributed to significant soil lead contamination in the U.S. from the early 18th century to the 2010s. According to United States Geological Survey (USGS) report, in 2021, ten active lead mines in the U.S. produce lead as a principal product or byproduct (USGS, 2021). Since the last lead primary lead refinery closed in 2013, most lead mine production in the U.S. has been moved out of the U.S. Until January 2021, only 12 secondary refineries were operating in the U.S. (USGS, 2021). In addition to industrial lead emissions, another historical source that contributed to the lead deposition in the soil was the past use of leaded gasoline. In comparison, the primary contemporary sources of soil lead include weathering of exterior lead-based paint, leaded ammunition, leaded battery manufacturing, and auto repairing.

Lead-contaminated soil can indirectly and directly contribute to human blood lead concentrations and is highly associated with severe lead poisoning. The dominant mechanism of lead exposure appeared to be the indirect soil-to-dust-to-blood pathway (Mielke and Reagan, 1998). This mechanism commonly happens as the outdoor lead-contaminated soil is tracked indoors on shoes, contaminating the interior dust. The inhalation or ingestion of the contaminated dust lead to elevated blood lead levels among children and adults. Another pathway of human soil lead exposure is direct ingestion. Specifically, children have the tendency to put their hands or other objects, which could be contaminated with lead soil particles, into their mouths, thus increases the opportunity for their ingestion of lead-contaminated soil. Children can absorb about 50% of the ingested lead after a meal and up to 100% on an empty stomach (ATSDR, 2017).

Several regulatory and recommended soil lead standards were issued nationwide and regionally. According to the EPA standards, a soil lead hazard is characterized as bare soil on residential property or child-occupied property that contains total lead equal to or exceeding 400 parts per million (ppm) in a play area and 1,200 ppm for non-play areas (U.S. Environmental Protection Agency [EPA], 2000). This regulation also applies to cleanup projects that use federal funds. The most stringent soil lead regulatory standard in the U.S. is set by the California Office of Environmental Health Hazard Assessment (OEHHA) and the Department of Toxic Substances Control (DTSC). The California DTSC currently uses the value of 80 ppm as the screening level for California residential, or unrestricted, land use (Department of Toxic Substances Control [DTSC], 2018). According to DTSC, soils with a total lead concentration of 80 ppm or less are considered acceptable (DTSC, 2018). Furthermore, the American Association of Pediatrics (AAP) recommends that soil contains lead concentration less than 50 ppm is more protective for children (American Association of Pediatrics [AAP], 1993). However, this value is for guidance only and not enforceable.

Lead in indoor dust

A significant pathway of childhood exposure to lead is to ingest indoor dust that is lead-contaminated. Besides tracking-in of lead-contaminated soil, the main source of lead in indoor dust is deteriorating lead-based paint.

For centuries, lead was added to paint with the earliest records indicating the Romans use of lead compounds for glazing pottery (Hernberg, 2000). Certain lead compounds, such as white lead, lead (II) carbonate, and vivid yellow lead chromate, were used as colored pigments (Crow, 2007). Adding these specific lead compounds to the paint can create specific colors, hasten drying, and produce a more durable and moisture resistant paint product (Shetty, 2019). Starting from the early 1900s and peaking in 1922, lead was a common component found in U.S. paint products and used widely until a nationwide ban on lead-based paint was introduced by the Consumer Product Safety Commission (CPSP) in 1978 (Shetty, 2019; U.S Consumer Product Safety Commission [CPSP], 1977). However, this legal action did not fully or immediately terminate the use of lead-based paint. Jacobs et al. found that about 3% of houses built between 1978 and 1998 had some exterior components painted with lead-based paint, and 1% of these houses had interior surfaces painted with leaded-based paint (Jacobs et al., 2002).

Historically, lead-based paint was regarded as the greatest contributor to lead poisoning. Some findings from environmental lead exposures to BLL pathway analysis suggested that lead-based paint was a more significant contributor than lead-contaminated soil (Lanphear et al., 1996). Ingestions of deteriorated paint chips and lead-based paint contaminated dust were the major pathways for children exposed to lead-based paint. Older homes, especially those built by 1978, have a higher likelihood of having lead-based paint. According to the U.S. EPA, approximately 24 million housing units in the U.S. have significant lead-based paint hazards, including deteriorated paint and lead-contaminated house dust. About 4 million of these are home to young children (CDC, 2020).

The amount of lead in floor and windowsill dust is used to determine residential and childcare site lead in paint hazards. In order to better protect children from the adverse health effect of lead exposure, the U.S. EPA tightened the standards for lead in dust on floors and windowsills in 2019. The current standards are ten micrograms (µg) of lead in dust per square foot (ft^2) for floor dust and 100 $\mu g/ft^2$ for windowsills. In contrast, the former lead dust hazard standards were 40 $\mu g/ft^2$ for floor dust and 250 $\mu g/ft^2$ for windowsills (U.S. EPA, 2020a). Nevertheless, some researchers suggested the revised lead in dust standards were not adequately protective for children (Braun et al., 2020). A cohort study conducted in Cincinnati, Ohio found that children who lived in the households at the EPA revised floor and windowsill dust standards of 10 and 100 $\mu g/ft^2$ were having 45% and 33% higher risk of presenting a BLL ≥5 µg/dL, compared to the children who lived at homes with more stringent standards of 5 $\mu g/ft^2$ for floor dust and 50 $\mu g/ft^2$ for windowsill dust, which were set up by the researchers (Braun et al., 2020).

Overall, historic lead-based paint and lead in dust remain a public health threat in the U.S., particularly to children. Scientific research on the prevalence, distribution, and determinants of lead in paint and dust is necessary, as more informed policy and regulation establishments rely on scientific knowledge and findings.

Lead in air

Lead is one of the six major air pollutants listed by the World Health Organization (WHO, 2019; Manisalidis et al., 2020) and the U.S. National Ambient Air Quality Standards (NAAQS) (U.S. EPA, 2021a). Historically, lead emissions from mining, smelting, refining operations, and leaded gasoline led to significant air pollution and posed a significant public health problem. The Clean Air Act, which the U.S. Congress enacted in 1970, contributed to eliminating leaded gasoline in the U.S. and reducing industrial lead emission (U.S. Congress, 1970). According to the U.S. EPA air quality national summary, in 2020, concentrations of lead in the air have decreased by 98% compared to 1980 (U.S. EPA, 2021b).

The largest present sources of lead released to the air include piston-engine aircraft that used leaded aviation fuel and metal processing facilities. The highest air concentrations of lead are usually found near lead mines and smelters (U.S. EPA, 2021c). The U.S. EPA uses an Air Quality Monitoring System (AQS), which collaborates with state, tribal, and local agencies to measure lead concentrations using air quality monitors. Data consistently collected by the AQS were used to present the air quality trends for lead and thus ensure lead is at regulatory levels which will not bring harmful effects on public health and the environment (U.S. EPA, 2021c). The current NAAQS standard of lead is not to be exceeded 0.15 micrograms per cubic meter on a rolling three-month average (U.S. EPA, 2021a).

Although the AQS provides comprehensive and publicly available lead in air monitoring data and other non-AQS air monitoring data is available, literature reported lead concentrations in the air was limited (Frank et al., 2019). Available lead in air research in the U.S. did not report any air samples containing a lead level exceeding the NAAQS standard. However, a systematic review suggested air lead studies between 1996 and 2016 in the U.S. focused on indoor air reported a significantly higher lead concentration than those focused on outdoor air (Frank et al., 2019). Therefore, additional research on lead in indoor air is necessary to better characterize the sources of indoor air lead and understand the potential impacts (Frank et al., 2019).

Childhood lead poisoning

History and pathology

Childhood lead poisoning was first described in 1892 (Gibson et al., 1892; Needleman, 1999). However, it was not until about 100 years later that researchers and physicians comprehensively understood childhood lead poisoning. The first strategic childhood lead toxicity prevention plan was carried out by the U.S. Centers for Diseases Control and Prevention (CDC) in 1991 (Roper et al., 1991; Needleman, 1999). Lead is highly toxic to children and causes significant adverse health effects, including physical and neurologic damages (Bellinger, 2008; Gould, 2009; AAP, 2016). There is no safe level of lead exposure. For example, extremely high BLL (over 100 µg/dL) can lead to protracted vomiting, brain damage, and even death (AAP, 2016; Woolf et al., 2007). Even low levels of lead can affect multiple body systems and development. According to the AAP, children with BLL less than five µg/dL may also show diminished intellectual and academic abilities and demonstrated neurobehavioral disorders (AAP, 2016). Furthermore, no treatment is recognized as effective in fully correcting many lead-related health effects (Markowitz, 2000; AAP, 2016). Once lead-related damage has occurred, children often suffer lasting adverse health effects (Markowitz, 2000; AAP, 2016).

Same as adults, lead enters children's bodies by three major pathways: direct ingestion through the gastrointestinal tract, inhalation through the respiratory tract, and dermal absorption through the skin. It is recognized childhood lead poisoning is primarily a result of exposure by ingestion of lead particles, compared to adults whose primary pathway is inhaling lead fumes (AAP, 2016; Papanikolaou et al., 2005). The main reason is children's activities, such as hand-to-mouth activity, increased their exposure to environmental contaminants (Bornschein et al., 1985; Bellinger et al., 1986).

Researchers also found that more inadequate hand hygiene practices were associated with elevated BLL, hand lead levels, and lead levels on food (Bellinger et al., 1986; Freeman et al., 1997). Furthermore, children usually have higher absorption rates through their gastrointestinal tract than adults because of their age and nutrition status. An average healthy adult usually absorbs an average of 10 to 15% of the ingested quantity. In contrast, this amount can increase to 50% or even 100% for infants and young children when they have an empty stomach (Papanikolaou et al., 2005; Haputman et al., 2017)

Prevalence of childhood lead poisoning in the U.S.

Childhood lead poisoning has been a significant public health concern in the U.S. due to its long history of lead mining and usage. In the 1970s, an estimate of 88% of U.S. children who were younger than six years old had a BLL ≥10 μg/dL (Pikle et al., 1994). After a series of legal actions on lead-based products, children's BLL has dramatically declined. By the early 1990s, the estimated percentage of BLL ≥10 μg/dL decreased to less than 5% among U.S. children who were younger than six years of age (Bernard and McGeehin, 2003) The most recent CDC national childhood blood lead surveillance data indicated that only 2.0% of children younger than six years old have BLL ≥5 μg/dL (CDC, 2019).

Roles of the U.S. agencies in preventing childhood lead poisoning

Despite the significant decline in children's BLL nationwide, lead poisoning remains a challenge to the U.S.; government agencies have been dedicated to reducing and eliminating childhood lead poisoning. The U.S. CDC operates a Childhood Lead Poisoning Prevention Program, which includes strengthening blood lead testing, reporting, and surveillance, linking exposed children to recommended services, and targeted population-based interventions (CDC, 2021a). An important mission of the CDC has been identifying and setting up reference BLL. The reference value of BLL has been substantially decreasing over the past decades, as effects of lead poisoning were found at lower BLLs. The CDC updates the BLL reference value every four years using the 97.5th percentile of children's BLL distribution from the latest two National Health and Nutrition Examination Surveys (NHANES) (U.S. CDC, 2012). In 2012, the Advisory Committee on Childhood Lead Poisoning Prevention of the CDC concluded that there is no safe level of lead exposure. In that same year, a reference BLL value of <5 μg/dL was adopted (U.S. CDC, 2012).

The U.S. Environmental Protection Agency (EPA) has also prioritized reducing childhood lead exposure as one of the agency's missions (U.S. EPA, 2020b). The U.S. EPA's main efforts were to regulate the lead hazard standards, including reviewing and updating lead regulations on lead in paint, dust, and soil, lead in water, lead in air, and lead in waste disposal (U.S. EPA, 2020b). Since the 1970s, the EPA has made tremendous efforts to lower environmental and children's blood lead levels. The highlight of EPA's actions included the 1973 phase out of lead in automobile gasoline, the 1986 Safe Drinking Water Act, and the 2001 hazard standards for lead in paint, dust, and soil. In 1980, the U.S. Congress established the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), which established the federal Superfund program administered by the EPA (U.S. Congress, 1980). The Superfund program allowed EPA to clean up hazardous waste sites and responded to significant environmental emergencies across the U.S. Lead is one of the significant hazards listed on the Superfund program's priority list. At lead Superfund sites, EPA aims to limit the risk of children having a BLL ≥ 10 μg/dL by either addressing the emission of lead or treating the lead-contaminated media (U.S. EPA, 2020c). In Omaha, Nebraska, the Omaha lead Superfund site declared by the U.S. EPA in 1998, was one of the largest Superfund sites in the EPA Superfund program history.

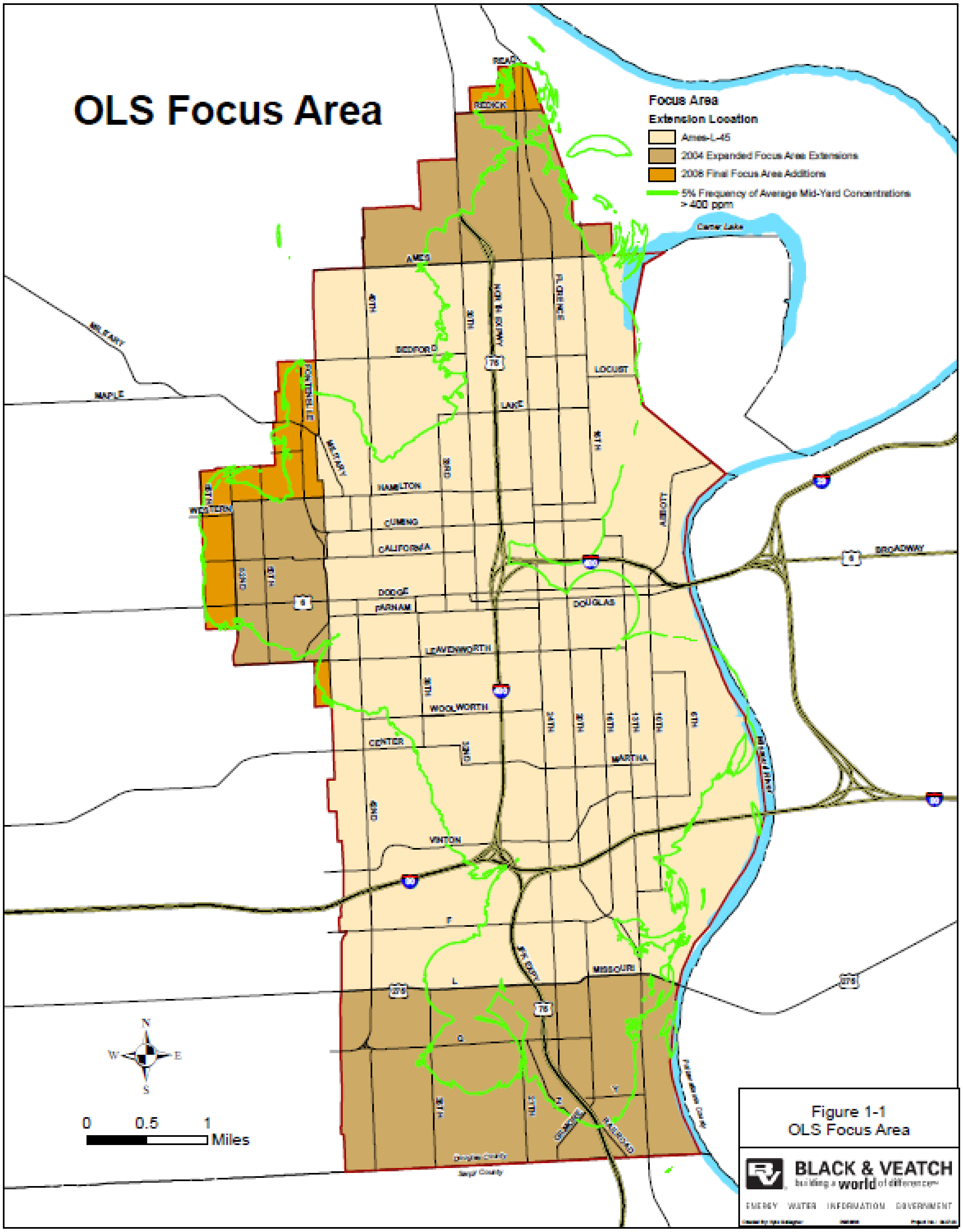
Lead poisoning in Omaha, NE

History of Omaha Superfund Site

Between 1998 and 2015, the U.S. EPA sampled the soil of more than 40,000 residences in the Omaha area and found that about 33% of the properties had soil lead levels above the EPA residential property's soil lead hazard standard of 400 ppm. These levels are in stark contrast to a typical non-contaminated home's soil lead level of 10 to 50 ppm (ATSDR, 2017). Based on the findings, the EPA declared 8,840 acres of Omaha a Superfund site, the largest residential Superfund site in the U.S. (U.S. EPA, 2021d; U.S. EPA, 2016; Figure 2.1). The Omaha lead Superfund site contains residential properties, public parks, and childcare facilities. Due to the history of lead contamination, environmental media in the Superfund site, such as soil, has been heavily contaminated.

Over 125 years, more than 100 businesses, including lead smelting and refining facilities, manufacturing companies, and battery recycling plants, have contributed to lead contamination in Omaha (Fletcher, 2016; U.S. EPA, 2021d). For example, the American Smelting and Refining Company, inc. (ASARCO) operated one of the largest lead refineries in the world on the bank of the Missouri river, releasing massive amounts of lead into the air, water, and ground in Omaha between 1889 to 1997 (Fletcher, 2016). In addition, a lead battery recycling plant operated by Aaron Ferer & Sons Company and later the Gould Electronics, Inc., had also been releasing lead-containing particles to the atmosphere for over 30 years (Fletcher, 2016; U.S. EPA, 2021d).

Figure 2.1. Map of Omaha Lead Superfund Site (Source: U.S. EPA, 2021d).



Historical children's blood lead levels in Omaha, NE

The earliest Omaha blood lead study found an average of 25.6 μg/dl BLL for 204 young children who lived in the urban mixed areas and an average of 14.6 μg/dl BLL for 38 young children who lived in the suburban areas (Angle et al., 1984). These average BLLs were significantly higher than the regulatory standards at the time (Angle and McIntire, 1979; Angle et al., 1984). In the early 1990s, the EPA learned that approximately 40% of the residential children had elevated blood lead levels in some areas of eastern Omaha. Research also found that over 25% of the children between 0-72 months who lived in Douglas County (of which Omaha is the county seat) had BLL greater than ten μg/dl (U.S. EPA, 2021d). While historic factories and businesses like ASARCO and Gould Electronics, Inc., have largely relocated out of Omaha, the legacy of lead pollution remains in topsoil due to its stability in the environment and poses a risk to residents of Omaha.

Current status and issues

In 2015, the EPA declared that the EPA-lead remediation of lead in soil program was completed for the Omaha Lead Superfund site. The cleanup activities were completed for 93% of the qualified properties, and thus, EPA partially removed the Omaha Lead Superfund site from the EPA's list of national priorities. In 2017, EPA collected 1.1% of the 20,080 children aged 0-84 months in Douglas County and found 1.53% of these children had BLL greater than the CDC's revised BLL standard of five μg/dL (U.S. EPA, 2021d; Klemick et al., 2020). This result is lower than the finding of 3% of children who exhibited BLL ≥5 μg/dL in a six-year retrospective national study on children younger than six years old (McClure et al., 2016; ATSDR, 2005). The most recent available Nebraska Department of Health and Human Services (NE DHHS, n.d.) blood lead level data in 2015 showed that among 17,800 tested children aged 0-5 in

Douglas County, 164 (0.9%) children had an BLL≥5 μg/dL. However, there were a couple issues with these children's BLLs reports: 1) the measuring methods may not be accurate. For example, the number of 17,800 from the NE DHHS's report included both confirmed and unconfirmed blood lead tests, so the validity of estimated percentage was questionable; 2) a certain age group of children's BLL remain uninvestigated. Reports from EPA and NE DHHS only included children aged 6 years or younger, the BLL status among children older than 6 years of age was unknown; and 3) most of children living in the Greater Omaha area had not received blood lead tests. According to Douglas County Health Department, the children (age under 18) population was 142,366 in 2015 (Douglas County Health Department [DCHD], n.d.). Therefore, the NE DHHS data only covered about 12.5% of children in the Douglas County. The EPA study only collected 1.1% of the children aged 0-6 years. There remains a knowledge gap on current Omaha children's blood lead status, especially for children living in the Omaha Lead Superfund site.

In addition to the lack of children's blood lead information, Omaha children may still be exposed to environmental lead sources. Researchers from the University of Nebraska-Lincoln found elevated lead levels in community garden soil and vegetables (Sangster et al., 2012). Our preliminary data also showed residents in the Omaha Lead Superfund site were more likely to be exposed to elevated indoor lead dust (Qin and Achutan, 2021). Additionally, residents in Omaha were concerned the EPA standards of environmental lead exposure may not be protective enough, because of local case reports and national research findings (Braun et al., 2020; U.S. EPA, 2019). For example, in the EPA's second five-year report for the Omaha Lead Superfund site, the EPA admitted that the cleanup levels for residential yards might not protect children to the current CDC's reference value of blood lead levels (U.S. EPA, 2019).

Benefit of research

By achieving the objectives of this dissertation, we will provide updates and valuable information on lead exposure and poisoning for public health professionals, city planners, government leaders, and residents. Public health professionals can use our findings to identify future research directions to characterize lead poisoning issues better locally, nationwide, and globally. City planners and government leaders will be able to better understand the current lead poisoning status and benefits of a healthier environment, which will be helpful in facilitating future city planning and policymaking. Last but not least, our research will provide essential information for residents who are concerned about their household lead concentration and the risk of lead poisoning. We hope the findings and recommendations of this dissertation will contribute to better outcomes on both environmental and community health in Omaha, Nebraska.

CHAPTER 3: ASSESSMENT OF SOIL AND AIR LEAD CONCENTRATIONS IN OMAHA PUBLIC PARKS

Abstract

Background: Soil and air have been identified as major sources of lead exposure in Omaha, Nebraska. The purpose of this study was to quantify the current soil and air lead concentrations in Omaha public parks. Methods: There are 58 parks within the Omaha Superfund site and 163 parks outside the Omaha Superfund site. We conducted one preliminary study (ten Superfund site parks) and one full-scale study in a random sample of 60 parks (30 inside the Omaha Lead Superfund site and 30 outside). Soil and air samples were collected from or near children's populated areas at each park. We compared different groups' lead concentration statistics and examined whether each park’s distance to the nearest highway and atmospheric parameters during the sampling were correlated with soil lead concentration. Results: A median soil lead concentration of 33.1 parts per million (ppm) from 30 Superfund site parks from the full-scale study was higher (p-value<0.0001) than the median lead concentration (14.0 ppm) from those 30 non-Superfund site parks. The median historical lead concentrations from 24 parks inside of the Omaha Lead Superfund site was 132.7 ppm, which was significantly higher than their current median lead concentration of 33.1 ppm ($p<0.0001$). All air samples were below the limit of detection. An insignificant decline of soil lead concentration was found among the Superfund site parks as the park's distance to the nearest highway increases (Pearson's $R=-0.164$, $p>0.05$). Conclusion: Soil lead concentrations were significantly higher in the Omaha Lead Superfund site parks, compared to non-Superfund site parks. We recommended continuous monitoring on lead concentrations in different environmental media, such as dust on playground equipment.

Keywords: lead exposure, soil, air, parks.

Introduction

Surface soils and air in many U.S. cities have been contaminated with lead which pose threats to population health. There are three major anthropogenic sources that contribute to the lead deposition in the soil and emissions into the air: 1) industrial point sources, such as historical smelting and refinery operations, coal power plants, and manufacturing of lead batteries, automobiles, ships, solder, and lead pigments; 2) legacy sources, such as lead-based paint and leaded gasoline; and 3) contaminated consumer products, such as ceramic cookware, imported spices, cosmetics, herbal medicines, and leaded ammunition (Harrison, 1981; Ab Latif Wani, 2015).

Industrial operations were the primary lead contamination source in Omaha. Over the course of 125 years, more than 100 businesses, including lead refineries, factories, copper smelters, and battery recycling plants, have emitted large amounts of lead into the air, contaminating the soil in a 27-square mile area (U.S. EPA, 2021d). Although these factories and businesses have largely relocated out of Omaha, the legacy of the lead pollution remains in topsoil due to its stability in the environment. Between 1998 and 2015, the U.S. Environmental Protection Agency (EPA) sampled the soil of more than 40,000 residences in the area and found that about 33% of the properties had soil lead levels above 400 parts per million (ppm). These levels are in stark contrast to a typical non-contaminated home's soil lead level of 10 to 50 ppm. As such, these findings led the EPA to declare 8,840 acres of Omaha a Superfund site, the largest residential Superfund site in the U.S. (U.S. EPA, 2021d; ATSDR, 2005)

Historically, lead-based paint was regarded as the number one problem in lead poisoning in the U.S. (Lofgren et al., 2000; Mielke and Reagan, 1998) However, after decades of effort, researchers proved that soil lead is also highly associated with severe lead poisoning (Ab Latif Wani, 2015; Mielke and Reagan, 1998; Mielke et al., 2019). In some cases, researchers recognized that elevated BLL among both children and adults were caused by high concentrations of lead in dust and soil when lead-based paint was completely absent in the environment (Patrick, 2006; Mielke et al., 2019). Additionally, researchers also suggested that soil lead may be more important than lead-based paint as a pathway of human lead exposure because evidence showed that the soil-to-dust-to-blood pathway appears to be the dominant mechanism of childhood lead exposure (Xintaras, 1992; Mielke and Reagan, 1998; WHO, 2010). Another pathway of human soil lead exposure was ingestion. Specifically, children have the tendency to put their hands or other objects into their mouths. These objects could be contaminated with lead soil particles, thus increasing the opportunity for their ingestion of lead-contaminated soil. Children can absorb about 50% of the ingested lead after a meal and up to 100% on an empty stomach (ATSDR, 2017).

Another large source of lead contamination in the U.S. is the historic leaded gasoline (Mielke et al., 2001; Newell and Rogers, 2003). Tetraethyl lead was added into gasoline to prevent engine knocking and valve seats from wearing and tearing. Although, the U.S. Environmental Protection Agency (EPA) banned leaded gasoline use for on-road vehicles in 1996 (U.S. EPA, 1996a), legacy lead from the leaded gasoline can still be found in the roadside soil today (Pavilonis et al., 2020; Mielke et al., 2001). Studies suggested heavy lead contamination of surface soil was positively associated with street length density and proximity to highways (Fakayode and Onianwa, 2002; Pavilonis, 2020).

In December 2015, the EPA declared that they completed lead soil remediation for 93% of the qualified Omaha residential properties and thus terminated the EPA-lead action at the Omaha Lead Superfund site (U.S. EPA, 2021d). However, the effectiveness of such soil remediation programs on children's BLL has been contradictory. Lanphear et al. conducted two cross-sectional surveys before and after a three-year soil remediation program. They found the program was significantly associated with a BLL decline among children who lived near a former smelting and milling operation (Lanphear et al., 2003). However, another study conducted in a similar period by Farrell et al. indicated that soil lead abatement was not able to lower the children's BLL in Baltimore, MD (Farrell et al., 1998). In 2000, the U.S. EPA held a symposium on lead remediation effectiveness and determined there were two major measures to assess the lead remediation success: 1) a reduction in blood lead concentrations of the most susceptible subpopulation of residents (usually children); and 2) a reduction in the lead concentration of soil and dust, which were the major pathways of lead exposure. However, researchers also pointed out that neither of these measures adequately evaluates the long-term effectiveness of remediation (U.S. EPA, 2000a; Mushak, 2003). The most recent review of the U.S. lead intervention program was conducted by an international organization named The Cochrane Collaboration. In this review, the researchers concluded that the U.S. program is ineffective for reducing children's BLL. Furthermore, the review demonstrated that they were unable to review soil abatement and its combination interventions' effectiveness on children's BLL because insufficient data exist (Nussbaumer-Streit et al., 2016).

Despite efforts in controlling soil lead in residential areas, research and intervention on recreation-related soil lead are lacking. Public parks in urban cities have been considered important assets for childhood physical and social development. However, the presence of environmental lead exposures in public parks poses negative effects on children's health. Because of weathering and time, lead-based paint on park playground equipment can deteriorate into chips and dust that contain lead and thus pollute the park soil. Between 1996 and 2008, the U.S. Consumer Product Safety Commission carried out a random sampling of paint from playgrounds in 13 cities, and

11 of them had playground equipment above lead hazard control measures (U.S. CPSC, 1996, 2007). Besides deteriorated lead-based paint, soil in Omaha public parks may also be contaminated by the legacy lead from the industrial operation and leaded gasoline usage. However, there were only a handful of studies carried out in the Omaha area aiming at recreational soil lead concentrations.

Insufficient data and unclear effects of soil treatment programs on children's BLL necessitate further research and assessments of soil and air lead exposures' effects on children. The objectives of this study were to fill the data gap of recreational soil lead concentrations and improve the understanding of current environmental lead exposures' distribution in Omaha, NE. The central hypothesis of this study was those lead concentrations in soil and air are significantly higher among parks located inside of the Omaha Lead Superfund site compared to those located outside of the Omaha Lead Superfund site. To achieve these objectives, we conducted a preliminary study (Study 1) to measure soil lead concentration in public parks inside the Omaha Lead Superfund site and a full-scale study (Study 2) to investigate lead in soil (Study 2-a) and air (Study 2-b) in public parks across the Greater Omaha area. Furthermore, we performed spatial analysis on data of soil lead and presented the findings based on geographical subgroups determined by the Omaha Lead Superfund site.

Methods

Study site and eligibility criteria

Eligibility criteria

There are 221 parks in Omaha, NE. Based on the Omaha Lead Registry's Superfund site program map (City of Omaha, n.d.a). We determined there are 58 parks inside the Omaha Lead Superfund site and 163 parks outside. The eligibility of sites included: 1) the parks must be located within the city of Omaha; 2) the parks must have a public area with soil that allows for soil sampling; and 3) the parks must have at least one play area. Play area is defined as an area of frequent soil contact by children of less than six years of age as indicated by, but not limited to, such factors as the following: the presence of outdoor play equipment (e.g., sandboxes, swing sets, and sliding boards), children's possessions and/or observations of children's play patterns (Department of Housing and Urban Development [HUD], 2012).

Site selection per study

Study 1: Pilot project on soil lead concentration in Omaha Superfund Site public parks.

In October 2019, we evaluated soil lead concentrations in Omaha Superfund site parks. We used Dodge Street, the main street in Omaha that roughly divides the Omaha Lead Superfund Site into north and south, to determine the subgroups of this study. Among the 58 public parks inside the Omaha Lead Superfund site, there were 33 parks located north of Dodge Street and 25 parks located south of Dodge Street.

North and South Omaha have distinctive cultural and demographic characteristics. Approximately 56% of the Latinx residents live in the southeast part of the city, which is roughly the southern part of the Omaha Lead Superfund site. In North Omaha, there are multiple foreign-born minority populations. In recent years, this area has been settled by refugees.

Out of the 58 parks we excluded two before conducting randomization because these parks only had concrete tennis courts and no soil. We randomly selected ten parks, with five parks north of Dodge Street and five parks south of Dodge Street, respectively, by using the R Program (Vienna, Austria). We conducted walkthroughs at two parks for which there was not enough information from the City of Omaha public park roster to determine if they met the eligibility criteria. We also randomly selected three more parks from both north and south groups to use for potential replacements in case any parks from the original randomization did not meet our criteria. However, after conducting a walkthrough, we found all ten parks met the eligibility criteria.

Study 2: Assessment of lead concentrations in soil and air from Omaha public parks.

Study 2-a: Comparison of lead concentrations in soil between Superfund site and non-Superfund site parks.

We aimed to use the data from this study to 1) determine if the lead concentration in any Omaha public park's soil exceeded either the U.S. EPA standard for lead in bare soil in play areas (400 ppm) (EPA, 2000b) or the American Academy of Pediatrics (APP) recommended level of 50 ppm (AAP, 1993, 2016); and 2) evaluate if the soil lead concentration in Omaha Lead Superfund site parks is significantly higher compared to the lead concentration from the parks outside of Omaha Superfund site.

The goal of this study was to achieve at least 80% power using a Chi-square test at two-sided $\alpha=0.05$. Since EPA found about 33% of the soil samples exceeded 400ppm in the Omaha Lead Superfund site (U.S. EPA, 2021d), we hypothesized that about 30% of the soil samples from the parks inside of the Omaha Lead Superfund site would have a lead concentration equals to or higher than the EPA standard, and about 1% of the soil samples from parks outside of Omaha Lead Superfund site would fail to meet the standard. We determined a sample size of 60 parks for this study, with 30 parks each for Superfund site group and non-Superfund site group would give us enough statistic power to detect the hypothetical differences. We used SAS 9.4 (Cary, NC) PROC PLAN function to randomly select 30 parks plus five backup optional parks for each group. After randomization, we first checked the selected park's information based on the City of Omaha public park roster to determine if they met the eligibility criteria. If we determined a park did not meet our eligibility criteria, we randomly selected one from the backup list to replace it. For parks without clear amenities information, we then determined their eligibility by conducting site inspection and decided if a replacement was needed. There were three parks, one from the Superfund site group, and two from the non-Superfund site group, in our initial randomization not meeting the eligibility criteria and thus were replaced. We conducted the soil sampling for this study during August 2020.

Study 2-b: Determination of lead concentrations in the air from Omaha public parks.

We created a subset of air sampling sites from the same 60 parks that we conducted soil sampling. We randomly selected ten parks out of the 60 parks in Study 2-a for air sampling, with five parks from the Superfund site group and five parks from the non-Superfund site group. At each park, one researcher conducted a two-hour air sampling while another researcher collected soil samples concurrently. Both air and soil sampling for this study were conducted in September 2020.

Sample collection

Soil sampling

Sampling method

The sampling method for this study is adapted from the U.S. EPA soil screening guidelines and the U.S. Department of Housing and Urban Development (HUD) sampling method for lead determination in soil (U.S. EPA, 1996b; HUD, 2012). At each park, we took at least three individual samples from different sampling locations. We used a metal soil sampling probe to collect soil samples. All individual samples from each park's sampling locations were well mixed in a bucket and then the final composite sample was transported into a zip-type resealable bag for storage. The detailed sampling process is presented in Appendix 2.1.

In addition to soil sampling, we also measured temperature, relative humidity, and barometric pressure by using a direct reading instrument (QTRAK 7565x, TSI Incorporated, Shoreview, MN) at each park. These atmospheric parameters were collected immediately after the soil sampling and recorded on the site sampling field notes.

Sampling location

We chose play areas with playground equipment as the main sampling locations. A number of sampling locations were determined by the size of each park. For small parks (equal or less than 5 acres), three individual samples were collected to mix into a final composite sample, and in large parks (over 5 acres), a composite sample consist of at least six but not more than 30 individual soil samples.

In large parks without enough play areas (less than six sampling locations), three subsample locations were chosen. The location of subsamples depended on the pattern and extent of bare soil in the area being sampled. We typically took one subsample from the center of green space and another two subsamples from two different directions away from the center.

<u>Air sampling</u>

Sampling method

The air sampling method is based on Occupational Safety and Health Administration (OSHA) Method 1006 (OSHA, 2005). At each sampling site, we used a calibrated Airchek sampling pump (SKC Inc., Eighty Four, PA) at a flow of approximately 2 liters per minute to draw air through a mixed-cellulose ester (MCE) membrane filter (SKC Inc., Eighty Four, PA) with backup pad contained in a polystyrene cassette for two hours. We placed the sampling pump on a tripod at the height of 75 cm from the ground, which is the approximate breathing height of a child at play (Wilson, 2004). We secured the sampling pump on a tripod with zip ties and duct tape and then placed the sampling pump near the populated play areas. We also collected an ambient blank sample paired with each air sample for analysis and quality control.

Sample analysis

All soil and air samples were analyzed by an EPA accredited laboratory. Soil samples were analyzed by using the EPA Method SW6020 (U.S. EPA, 2014). Air samples were analyzed by using National Institute for Occupational Safety and Health (NIOSH) modified Method 7300 (National Institute for Occupational Safety and Health [NIOSH], 2003). The limit of detection (LOD) for soil samples is 2.4 ppm and for air samples is 0.2 ppm.

Statistical analysis

Descriptive statistics, including arithmetic means, geometric means, median, and range for soil and air lead concentrations, were calculated for all the parks combined, as well as separated by groups and geospatial sections. For 24 parks that had both current and historical soil concentrations, we used paired tests to compare their arithmetic and geometric mean soil concentrations, and median test to compare their median soil concentrations. The Mann–Whitney U test was employed to examine the statistical difference between soil lead concentrations by groups and geospatial proportions. Samples were below the LOD were replaced with LOD/√2 (Hornung and Reed, 1990).

We used Pearson’s correlation coefficients and simple linear regression models to predict geographic and atmospheric factors’ impact on soil lead concentrations. We used each park’s longitude and latitude to calculate their proximity of highway and examined the correlation between the distance to the highway with soil lead concentration. We measured the impacts of temperature, relative humidity, and barometric pressure on soil lead concentration by conducting both crude and adjusted linear regression models. All analyses were conducted in SAS® version 9.4 (Cary, NC), with the level of significance set at two-sided alpha=0.05.

Results

Descriptive statistics for lead concentrations in soil and air from Omaha public parks

A total of 80 composite soil samples were collected for this research project. The lead concentrations for all soil samples were below the EPA standard for lead in bare soil in play areas, a standard of 400 ppm. However, four samples from the Superfund site group had a lead concentration higher than 50 ppm, which exceeded the AAP recommended level. We did not detect significant lead concentrations in the air, as all ten air samples were lower than the limit of detection. Descriptive lead concentration statistics of all soil and air samples are presented in Table 3.1.

Table 3.1. Lead Concentration (ppm) in Omaha Public Parks' Soil and Air Samples.

Sampling groups and geospatial proportions	N	AM (SD)	GM (GSD)	Median	Range
Study 1					
Preliminary group soil total	10	31.6 (11.8)	29.5 (1.5)	28.6	15.0-47.8
North	5	30.5 (13.5)	28.1 (1.6)	25.8	15.0-46.2
South	5	32.6 (11.3)	31.0 (1.4)	31.4	20.5-47.8
Study 2-a					
Superfund group soil total	30	32.9 (15.6)	28.3 (1.9)	33.1	5.4-64.2
North	15	35.9 (16.0)	31.4 (1.8)	39.2	6.5-64.2
South	15	29.9 (15.0)	25.4 (1.9)	29.7	5.4-57.2
Non-Superfund group soil total	30	14.1 (4.9)	12.8 (1.7)	14.0	<LOD-25.3
North	12	13.2 (6.8)	10.8 (2.2)	15.6	<LOD-25.3
South	18	14.6 (3.2)	14.3 (1.2)	13.9	11.3-21.7
Study 2-b					
Subgroup soil total	10	31.6 (11.8)	29.5 (1.5)	28.6	15.0-47.8
Superfund subgroup	5	30.4 (2.4)	30.4 (1.1)	30.6	27.1-33.2
North	2	28.2 (1.5)	28.1 (1.1)	28.2	27.1-29.2
South	3	32.0 (1.3)	31.9 (1.0)	32.1	30.6-33.2
Non-Superfund subgroup	5	11.5 (12.7)	7.6 (2.7)	6.6	2.4-33.5
North	4	11.7 (14.6)	7.0 (3.1)	5.5	2.4-33.5
South	1	10.3 (NA)	10.3 (NA)	10.3	10.3
Subgroup air total	10	<LOD	<LOD	NA	<LOD
Superfund subgroup	5	<LOD	<LOD	NA	<LOD
Non-Superfund subgroup	5	<LOD	<LOD	NA	<LOD

Notes: ppm=parts per million; SD=standard deviation; GSD=geometric standard deviation; <LOD=under limit of detection.

Higher lead concentrations in Superfund site parks' soil

For soil lead concentration in 30 Superfund site parks, the median concentration was 33.1 ppm, which was 136% higher (p-value<0.0001) than the median lead concentration (14.0 ppm) in 30 non-Superfund site parks' soil (Figure 3.1). There were 24 parks from the Superfund site group with historical lead concentration records. Only one of these parks has a higher soil lead concentration than its historical record, the other 23 parks had a significant decline of soil lead concentrations (Table 3.2). The average and median historical lead concentrations among these 24 parks was 181.3 and 132.7 ppm respectively, which were significantly higher than the current mean and median lead concentrations of 33.0 and 33.1 ppm (p<0.0001).

Figure 3.1. Soil Lead Concentration (ppm) Comparison between Parks Inside of Omaha Lead Superfund Site and Parks Outside of Omaha Lead Superfund Site.

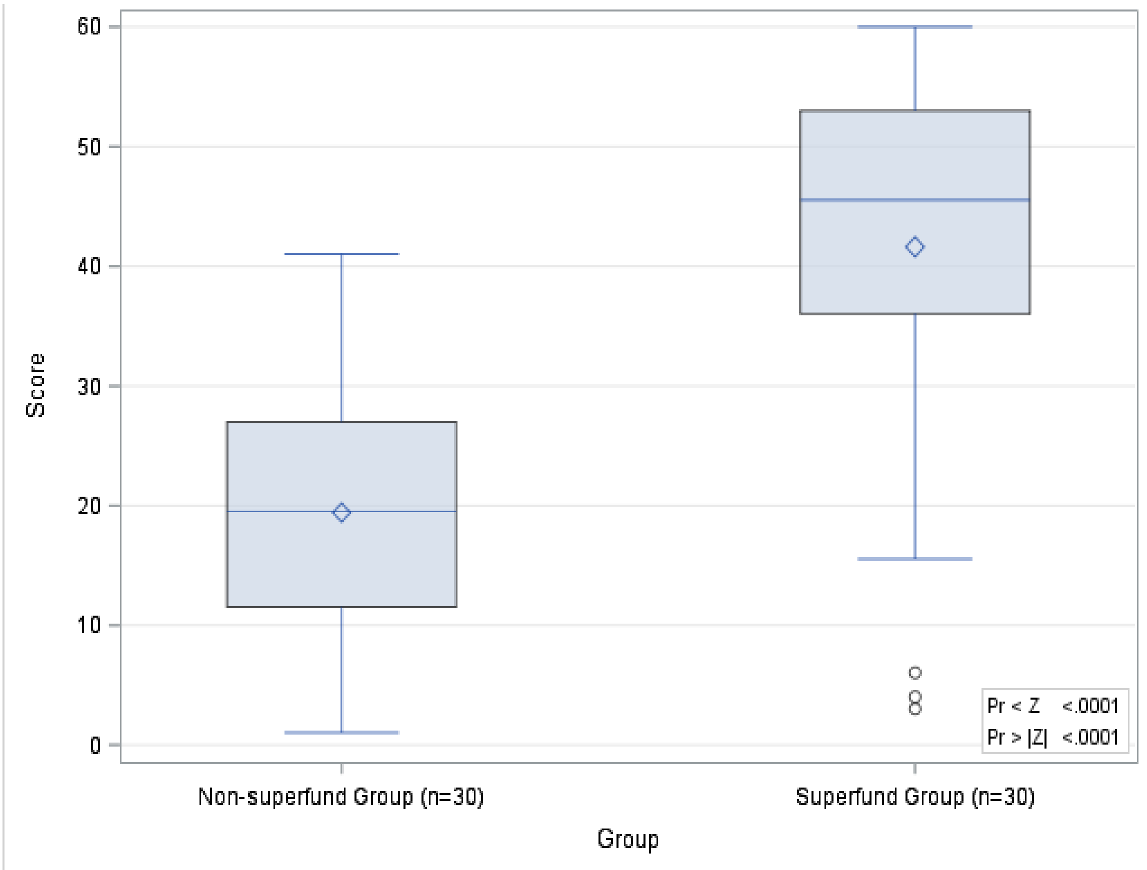


Table 3.2. Omaha Lead Superfund Site Parks' Current and Historical Soil Lead Concentrations (ppm).

		Current		Historical	
Park Name	**Zip Code**	**Soil Lead Concentration**	**Sampling Date**	**Soil Lead Concentration**	**Sampling Date**
Adams Park	68111	16.80	08/06/2020	76.95	08/10/2007
Albright Park	68107	39.20	08/12/2020	107.00	05/11/2006
Brown Park	68107	9.07	08/12/2020	80.80	06/22/2006
Christie Heights Park	68107	12.60	08/12/2020	56.70	08/17/1999
Clarkson Park	68131	49.20	09/01/2020	55.50	05/02/2006
Columbus Park	68108	46.30	08/12/2020	270.10	05/09/2006
Elmwood Park	68106	34.20	08/11/2020	NA	NA
Erskine Park	68111	49.80	08/10/2020	33.14	05/02/2006
Fillmore Park	68105	20.10	08/06/2020	NA	NA
Florence Park	68112	27.30	08/06/2020	NA	NA
Fontenelle Park	68104	39.20	08/10/2020	NA	NA
Hanscom Park	68105	23.90	08/12/2020	213.31	07/31/2007
Hitchcock Park	68117	5.37	08/12/2020	87.17	06/22/2006
James F. Lynch Park	68108	33.60	08/12/2020	143.80	06/22/2006
Kountze Park	68110	64.20	09/01/2020	217.32	01/03/2007
Levi Carter Park	68110	41.80	08/10/2020	400.00	09/04/2007
Lewis & Clark Landing	68102	50.70	08/10/2020	256.00	09/03/2014
Mandan Park	68107	57.20	08/12/2020	335.57	06/22/2006
Metcalfe Park	68104	26.00	09/01/2020	NA	NA
Miami Playground	68111	47.50	08/07/2020	87.00	03/26/2004
Miller Park	68107	19.80	08/06/2020	153.77	06/22/2006
Millers Landing	68110	6.49	08/12/2020	121.66	06/22/2006

Table 3.2. (continued). Omaha Lead Superfund Site Parks' Current and Historical Soil Lead Concentrations (ppm).

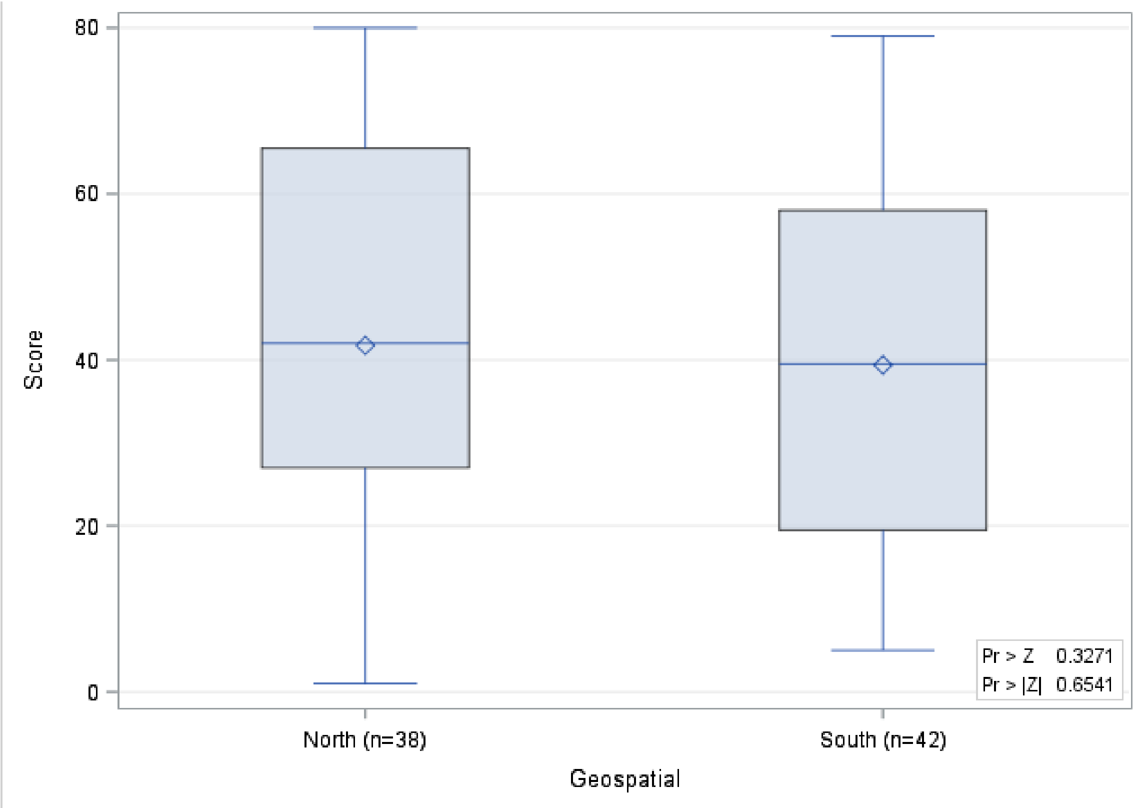
		Current		**Historical**	
Park Name	**Zip Code**	**Soil Lead Concentration**	**Sampling Date**	**Soil Lead Concentration**	**Sampling Date**
Norwick Park	68104	46.60	08/10/2020	NA	NA
Pulaski Park	68107	25.10	08/12/2020	42.03	05/09/2006
Spaulding Park	68111	50.10	08/10/2020	388.32	04/07/2006
Spring Lake Park	68107	29.70	08/12/2020	539.00	07/25/2007
Turner Park	68131	38.20	08/10/2020	398.46	05/12/2006
Unity Park	68107	20.80	08/10/2020	147.00	05/02/2006
Upland Park	68107	22.70	08/12/2020	64.80	06/22/2006
Yale Park	68111	32.60	08/11/2020	76.75	05/02/2006
Arithmetic mean (SD)		32.9 (15.6)		181.3 (140.5)	p<0.0001
Geometric mean (GSD)		12.8 (1.7)		135.8 (2.2)	p<0.0001
Median		33.1		132.7	p<0.0001

Notes: ppm=parts per million; NA=Not available; SD=standard deviation; GSD=geometric standard deviation.

Similar soil lead concentrations in the North and South Omaha

When comparing median lead concentrations between north and south Omaha (Figure 3.2), no significant difference (p=0.327) was found between the north (n=38) and south (n=42). Our preliminary study inside the Omaha Lead Superfund site indicated that the median soil lead concentration in the north (25.8 ppm) is slightly lower than the south (31.4 ppm; p-value=0.833). There was no statistical significance in the arithmetic and geometric mean concentrations either (Table 3.1). Additionally, when the number of Superfund site parks was expanded to 30 in our second study, we found that the median soil lead concentration in the north Omaha parks (39.2 ppm) is no longer lower compared to the south (29.7 ppm), but this difference remains insignificant (p-value=0.332). No statistical difference was found in the arithmetic means and geometric means between northern and southern Superfund site parks (n=15 for each area). These findings were consistent among those 30 non-Superfund site parks.

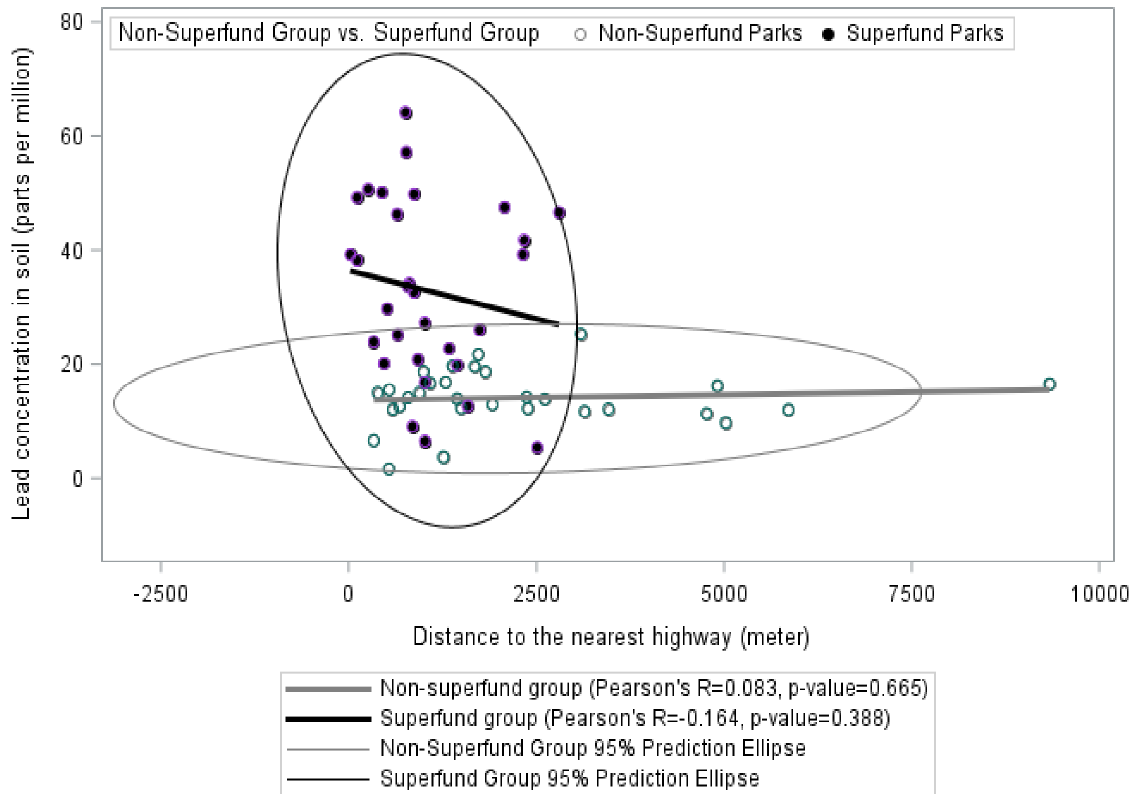
Figure 3.2. Comparison of Median Lead Concentration (ppm) for Public Parks in North and South Omaha.



Relationship between soil lead concentrations and park's proximity of highway

Parks outside of the Omaha Superfund site had a significantly longer average distance to the nearest highway (2,259.0 meters), compared to the parks inside of the Omaha Superfund site (1,044.0 meters, p-value<0.05). Each park's lead concentration and its distance to the nearest highway are presented in Figure 3.3. We found that park's distance to the nearest highway does not significantly impact lead concentration in the park soil (p-value>0.05). Although the correlation between distance to highway and soil lead concentration is not significant (p-value=0.388) among parks inside of the Superfund site, we observed a decline of soil lead concentration as the park's distance to the nearest highway increases (Pearson's R=-0.164).

Figure 3.3. Relationship between Omaha Public Park's Soil Lead Concentration and the Nearest Highway.



Atmospheric parameters' impacts on soil lead concentration

Temperature, relative humidity, and barometric pressure were measured during each park's sampling process except for the parks in our preliminary study. The average temperature, relative humidity, and barometric pressure were 28.1±4.2 Celsius of degree, 55.6±10.5 percent, and 29.8±0.3 inch of mercury, respectively. Among 70 available data points, we found that only barometric pressure has a negative crude association with the soil lead concentration (correlation coefficient=-0.024, t-value=-0.26, p-value=0.043). However, this association was diminished after adjusting for temperature and relative humidity (results not shown in table).

Discussion

All soil lead concentrations were below the EPA standard of 400 ppm for lead in bare recreational soil. Only four samples exceed the AAP recommended standard of 50 ppm. However, research indicated that even low lead levels in the blood can incur adverse health effects on children (Nigg et al., 2010; Taylor et al., 2011). Additionally, in the recent five-year review report of the Omaha Superfund site, the U.S. EPA claimed that "the cleanup level selected for residential yards (400 ppm) may not protect children to current CDC-acceptable blood-lead concentrations" (U.S. EPA, 2019). In other words, lead in the soil under the EPA's standard for bare recreational soil of 400 ppm could still lead to dangerous lead poisoning. Therefore, the U.S. EPA recommends that in places where the lead levels in bare soil are below the hazard standard, optional and modest soil treatment actions should also be considered (U.S. EPA, 2016). This is especially true if an area is populated with children six years and younger, or if the lead in the soil is suspected of contributing to elevated BLL among children in the area, soil treatment should be implemented.

A median concentration of 133.2 ppm was found for soil sampling activities in 24 Omaha Superfund site parks between 1999 and 2014, whereas the median concentration for the same 24 parks in our study conducted in 2020 was 33.1 ppm. Previous studies aiming at lead concentration movement and distribution in nonurban soils indicated that less than 0.1% of the mobile lead would migrate out of the topsoil each year (Bacon et al., 1996; Semlali et al., 2004). Theoretically, it will take about 700 years to decrease half of the lead in the top 16 to 20 cm nonurban soil. A study in New Orleans showed a 44% decrease in soil lead concentration over about 15 years (Mielke et al., 2019), which was much faster than the lead migration rate indicated in the nonurban soil lead concentration studies (Bacon et al., 1996; Semlali et al., 2004; Mielke et al., 2017). The decrease of soil lead concentrations in our study was similar to the findings of studies in nonurban soil lead (Bacon et al., 1996; Semlali et al., 2004; Mielke et al., 2017). There are two possible explanations to our finding. The first potential mechanism for lead reduction in either New Orleans or Omaha is associated with soil erosion due to the floods. Soil lead studies in New Orleans compared the lead concentrations in soil pre-and post- Hurricanes Katrina and Rita and found soil lead concentrations decreased significantly in flooded areas (Mielke et al., 2019, 2017; Pardue et al., 2005). Omaha was heavily impacted by the 2019 Midwestern U.S. floods (National Oceanic and Atmospheric Administration [NOAA], 2020). Some areas of the city, including the Superfund site, which is close to the Missouri River, had been impacted by the flood for seven to eight months. It is likely that some of the lead in the park soil was removed during the flood. However, in this study, we found parks not close to the Missouri River also showed a substantial decrease in soil lead concentration. Therefore, another potential reason for the lead reduction could the City of Omaha lead abatement programs in parks (City of Omaha, n.d.b).

Soil lead concentrations were thought to be significantly higher in the north portion of the Omaha Lead Superfund Site, according to the EPA and ATSDR assessment reports (ATSDR, 2005). There were two major reasons for this statement. First, the American Smelting and Refining Company (ASARCO) lead refinery that operated on the northeastern boundary of Omaha for over 127 years was identified as the primary source for soil contamination (U.S EPA, 2008; ATSDR, 2005; 2017). Second, ATSDR stated that the highest lead concentrations were likely to be along the direction of the prevailing winds, which in Omaha was northerly (approximately seven months of a year) (ATSDR, 2005). Results from our second study agreed with the ATSDR's statement, as the mean and median soil concentrations from north of the Superfund site parks were the highest among all four sampling groups. However, north Omaha parks' soil concentrations do not significantly differ from the other groups, and results from our preliminary studies showed soil lead concentrations were higher in the southern parks. These inconsistent findings suggest that it is necessary to re-evaluate the distributions and determinants of current soil lead in Omaha as the environment has changed and more advanced technology is now available.

We believe that future studies should examine up-to-date environmental circumstances and consider multiple potential determinants of lead. First, lead refinery businesses and factories like ASARCO were removed from Omaha a couple of decades ago, suggesting their current environmental impacts would differ from the previous status. Therefore, researchers cannot solely consider industrial point sources as the primary lead source in Omaha and ignore other potential sources of lead contamination. Secondly, researchers will need to consider introducing available and proper information, such as meteorological factors, into the studies and analyze these factors comprehensively. According to the National Oceanic and Atmospheric Administration

(NOAA), the most predominant wind direction is northerly in Omaha. However, the predominant average hourly wind direction varies throughout the year, and the prevailing north-to-south wind is more frequent during fall and winter (NOAA, 2021). Additionally, historical Omaha soil lead concentration reports suggested that the distributions of soil lead concentrations did not correlate well with either northerly or southerly prevailing wind directions. Our study also found that one park outside of the Superfund site had a soil lead concentration higher than the average Superfund site parks' concentration. These findings emphasize that researchers and responsible governmental organizations should comprehensively consider all potential lead sources and related determinants to have more valid assessments and develop lead prevention strategies across different geospatial portions of the city accordingly.

Automobile emission has been a major source of lead pollution in soils. Although leaded gasoline was banned for on-road vehicle use in the U.S. from 1995, legacy lead from the leaded gasoline can still be found in the roadside soil (Warren and Birch, 1987). Previous studies demonstrated that the distribution of heavy metals, including lead, in the soil near highways was significantly and inversely correlated with the increased distance to the road. In this study, we found no significant correlation between distance to the highway and soil lead concentration, which suggested the current automobile emission unlikely contribute to the lead pollution in park soils. We found an inverse correlation between distance to highway and soil lead concentration within the Superfund site parks. This inverse correlation was not significant, possibly due to the limited sample size. Therefore, we cannot completely reject the possibility of legacy lead from leaded gasoline is still a potential source of lead in today's public parks soil.

We also measured lead in the air in this study, but we did not find any air sample with a level of lead higher than the detection limit. Douglas County (where Omaha sits) is not currently monitoring atmospheric lead because the air quality monitoring program did not pick up any trace of atmospheric lead from 2011 to 2017 (DCHD, 2019). Our air sample findings are consistent with the air monitoring results. Previous research indicated that soil containing lead can become airborne, and thus, contribute to lead concentration in the air (Zahran, Laidlaw, McElmurry, et al., 2013; Zahran, Mielke, McElmurry, et al., 2013). Atmospheric soil is thus sensitive to high temperatures and barometric pressure, and low relative humidity (Zahran, Laidlaw, McElmurry, et al., 2013). Researchers have also shown that the air in the pores of the soil up to a depth of 6 inches is very similar in composition to the atmospheric air (Russell and Appleyard, 1915). Because we did not detect lead in the air samples, we sought to examine if atmospheric parameters have any impacts on soil lead concentration. However, our findings showed no significant association between any atmospheric parameters on soil lead concentration.

We found that there is a lack of hand hygiene stations in Omaha public parks. Evidence from previous research showed that inadequate hand hygiene practice was associated with childhood lead poisoning (Bellinger et al., 1986; Mahon, 1997; Freeman et al., 1997). We hope that city planners consider installing handwashing stations close to the playground and most populated areas in the parks. Lead prevention and hand hygiene educational signs can also be placed on these handwashing stations. Therefore, children and their parents who visited the parks can practice hand hygiene routinely. The installation of handwashing stations can be an easier method to reduce lead exposure, and it may require a lower cost to implement than soil abatement activities.

There are certain limitations to our study. Though sufficiently representing the most populated area of each park, the sampling locations at each park may not be representative enough for the whole park. Additionally, we used the approximate longitude and latitude of the sampling location, which was the closest to the nearest highway, to represent the whole park's longitude and latitude subjectively. Therefore, information and selection biases were introduced in the location metrics and each park's distance to the highway's determination.

Conclusion

None of the lead concentrations in Omaha park's soils exceeded the EPA standard level of 400 ppm. The median soil lead concentration in the Superfund site parks was significantly higher than that found in parks outside of the Superfund site. Evidence from other research and EPA reports showed that soil lead concentration lower than the EPA standard of 400 ppm may not be protective enough for a human. Therefore, further research is needed to verify the potential impact of current lead soil concentration on children's blood lead level, especially among children living inside of the Omaha Lead Superfund site.

CHAPTER 4: DISTRIBUTION AND DETERMINANTS OF ELEVATED RESIDENTIAL INDOOR LEAD DUST CONCENTRATION IN OMAHA, NE

Abstract

Background: Children's exposure to lead has been a longstanding concern in Omaha, Nebraska. This study aimed to examine whether a significant difference exists with residential indoor lead dust concentrations in homes inside the Omaha's Superfund site compared to those outside. Additionally, we aimed to identify the association between certain home and occupant characteristics and elevated residential indoor lead dust concentration. Method: We quantified windowsill and floor lead dust concentrations in 350 eligible household in Omaha, NE. We then conducted univariate and multivariate logistic regressions to analyze which home and occupant characteristics were associated with elevated lead dust concentration among 310 homes with completed data information. Results: Approximately 34% of homes in this study had a windowsill lead dust concentration higher than the EPA standard of 100 microgram per square foot (µg/ft^2) and about 31% of homes had a floor lead dust concentration higher than the EPA standard of 10 µg/ft^2. We found that homes inside of the Omaha Lead Superfund site had significantly higher indoor lead dust concentrations than those outside of Superfund site ($p<0.001$). Homes built before 1950 had the highest odds to have elevated levels of indoor lead dust (adjusted odds ratio [OR] =6.21; 95%CI: 2.32, 16.63). African American residents within the Omaha Superfund site had significantly higher odds (adjusted OR=2.22; 95%CI: 1.18, 4.18) of exposure to interior lead dust concentrations, compared to White Caucasians. Conclusion: Our findings suggest that indoor lead exposure is still a problem in Omaha. Findings from this study can provide knowledge of environmental health risk factors in the Omaha community.

Keyword: lead, indoor lead dust, childhood exposure, environmental health.

Introduction

Lead is one of the most prevalent elements in the environment. It is highly toxic to infants and young children (CDC, 2021a; 2019). There is no safe level of lead exposure; even low levels of lead can affect multiple body systems and development. Furthermore, there is no treatment recognized as effective in fully correcting many lead-related health effects (AAP, 2016). Therefore, removing children from lead exposure is critical to safeguard their health.

There are still many locations throughout the U.S. where a significant number of children are exposed to lead (CDC, 2021b). In Omaha, Nebraska, lead poisoning among children has been a longstanding public health concern. Between 1998 and 2015, the U.S. Environmental Protection Agency (EPA) found about 33% of 40,000 residences in the Omaha area had soil lead levels above 400 parts per million (ppm), and thus declared 8,840 acres of Omaha a Superfund site (U.S. EPA, 2021d). Hazardous substances, such as lead, have a profound adverse health effect on children and even more so among children living within Superfund sites, because young children are more likely to be exposed to lead in soil and dust (Lanphear, et al., 1998). In 2015, the EPA declared that the EPA-lead action of lead remediation in soil program was completed for Omaha Lead Superfund site, and thus partially delete the Omaha Lead Superfund site from the EPA's list of national priorities. Residential sites with no lead hazard cleanup activity required were removed from the eligible cleanup list of Omaha Lead Superfund site and current efforts within the original Omaha Superfund site were to obtain voluntary access to properties where the owner did not grant access to the EPA, which were led by the city of Omaha and the Douglas County Health Department. The EPA is still proving funding to soil and lead-based paint tests, and soil clean up actions if access is granted to the properties (U.S. EPA, 2021d).

Historically, lead-based paint is one of the major sources of indoor lead dust exposure in Omaha (ATSDR, 2005; Angle and McIntire, 1979; Angle et al., 1984). Lead-based paint was banned for indoor use in 1978. According to U.S. Department of Housing and Urban Development (HUD) survey, about 75% of homes built before 1978 contain some lead-based paint (U.S. HUD, 2011). Children who ingest chipped and peeled paint containing lead are at risk for lead toxicity and consequent developmental and medical problems (Min et al., 2007; Jusko et al., 2008). In addition, research from Lidsky et al. (Lidsky et al., 2006) and Landrigan et al. (Landrigan et al., 1987), further suggested serious health effects, such as brain injury with neuropsychologic dysfunction, and renal toxicity, were associated with lead dust toxicity. Older homes have a higher likelihood of having lead-based paint (Jacobs et al., 2002). Currently, over 63% of the housing within the Omaha Lead Superfund site was built before 1950; about 84,000 homes were built before 1978 across the Greater Omaha Area. Another source of indoor lead dust exposure is the lead from homes' soil. Evidence from a U.S. lead Superfund site in Bunker Hill, Idaho, showed that log-transformed house dust lead was significantly correlated with yard, neighborhood, and community soils lead levels (von Lindern, Spalinger, Bero et al., 2003). Other studies examined exterior soil lead influence on interior lead dust in the U.S. cities without a Superfund site also suggested that indoor lead dust concentration would be lower when house perimeter soil lead concentration decreased (Adgate et al., 1995; Clark et al., 2004). Although lead pollution in the soil may have been significantly decreased, there remains a lack of knowledge and understanding regarding lead dust concentrations from the interior of homes in Omaha, NE, and especially within the Omaha Lead Superfund site.

Residents who live in neighborhoods with dangerous levels of environmental exposure tend to have low sociodemographic status, for example being below the poverty line and having lower educational attainment (Ross and Mirowsky, 2001; Crowder and Downey, 2010). Specifically, in Omaha, these residents face many living challenges including but not limited to inadequate access to healthy food, inadequate education, and unsafe homes, leading to environmental justice issues (Reed, et al., n.d; Su, et al., 2017). Unclear indoor lead dust exposure status is problematic, particularly for families residing in Superfund site homes who are minorities and refugees with English language deficit, as they may not be aware of the risks associated with indoor lead exposures (Trotter, 1990; Pampel et al., 2010; Su et al., 2019). A previous study conducted in Milwaukee, Wisconsin, indicated that ethnic minority groups members were more likely to perceive lead exposure as a hazard, but their knowledge of lead exposure prevention was significantly less than majority group members (Griffin and Dunwoody, 2000).

A preliminary study that we conducted in 2020 found residents who lived in any of 12 zip codes that were partially or fully included in the Omaha Superfund site were more likely exposed to elevated indoor lead dust concentration, compared to those who live outside those zip codes. Additionally, several resident's socioeconomic status, such as household annual income less than the city's median level and lack of insurance coverage, were associated with elevated indoor lead dust concentration (Qin and Achutan, 2021). Some other researchers also suggested other specific socioeconomic status, such as poverty and lack of parental education were associated with high blood lead levels among children (Ahamed et al., 2005; Bellinger, 2008; Kim et al., 2018). However, it is still unclear whether certain socioeconomic characteristics possess direct or indirect effects on residents' indoor lead exposure and blood lead levels (Bellinger, 2008; Kim et al., 2018).

To better understand the distributions and determinants of elevated indoor lead dust status in the Greater Omaha Area, we acquired a more detailed profile of homes' indoor lead dust data and combined it with multiple Omaha public data sources. We developed the following two specific aims for this current study: 1) to describe residents' indoor floor and windowsill lead dust concentrations across the Greater Omaha area and compare indoor lead dust concentrations between homes inside of the Omaha Superfund site with the homes outside; 2) to characterize the relationships between home's and resident's characteristics with elevated indoor lead dust concentrations.

Methods

Study design

This is a cross-sectional study with secondary data analysis. We used the home's information and indoor lead dust concentrations collected by a local non-profit community organization, Omaha Healthy Kids Alliance (OHKA) as our main data. The OHKA started providing indoor lead risk assessment in the Greater Omaha area in 2012. The data used for this study were collected between 2013 and 2019.

Data management and variables

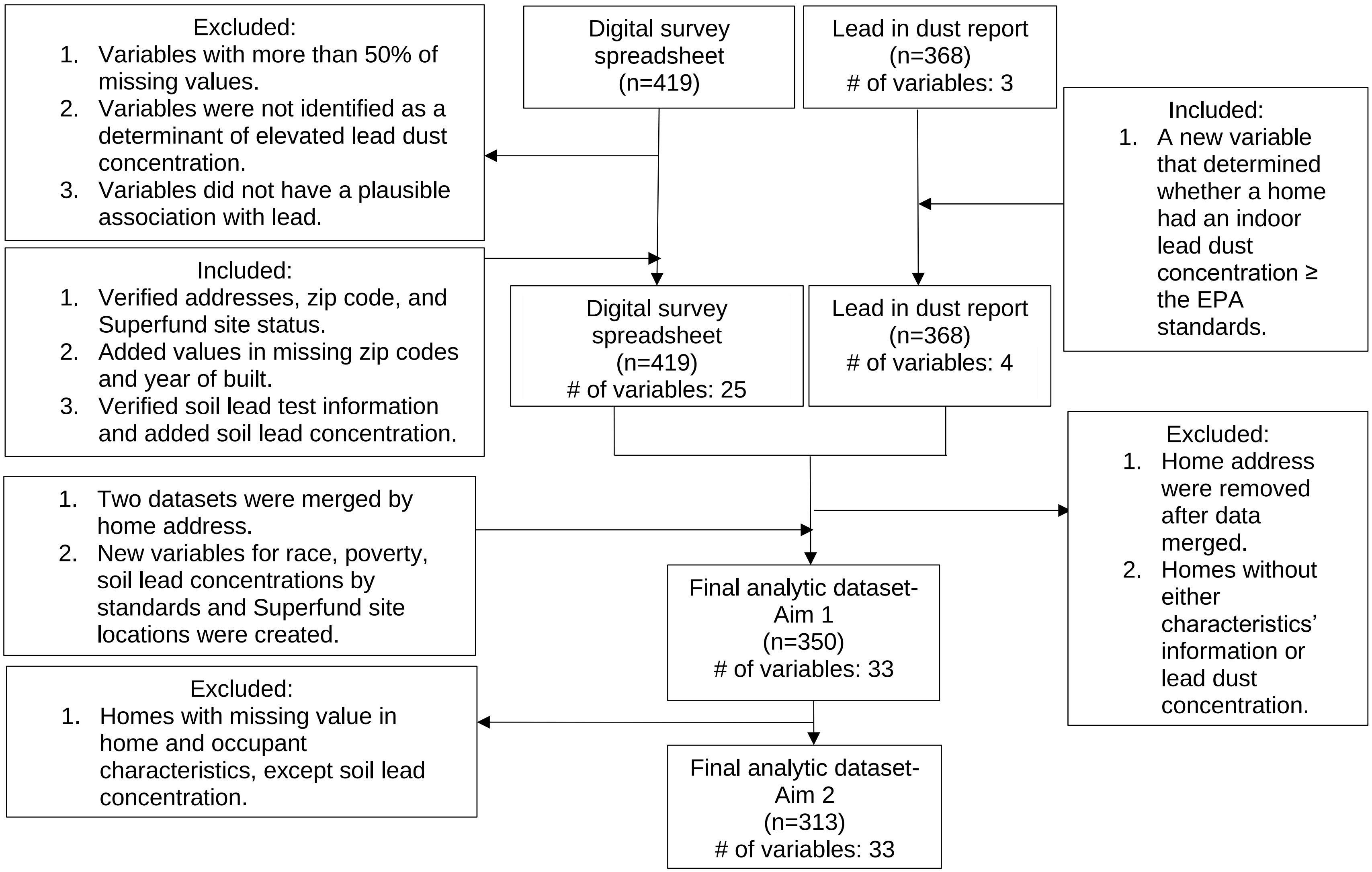
Data source

A spreadsheet containing digital survey results and lead in dust laboratory reports were provided by the OHKA. The digital survey was administered at each participating home when lead assessment was conducted. This survey was self-reported and included each home's and occupant's characteristics.

The lead risk assessment results for each home were presented in a lead in dust laboratory report. Each report contained each home's address, at least one windowsill and/or floor lead dust concentration. Both windowsill and floor lead dust concentration were measured in micrograms per square foot (μg/ft^2). The limit of detection (LOD) for windowsill and floor lead dust concentrations were 60 μg/ft^2 and 10 μg/ft^2, respectively.

After data management and quality control (Appendix B). We merged the home and occupant characteristics data with lead in dust report data by using the home address. The construction of final analytic dataset was presented in Figure 4.1.

Figure 4.1. Data Management Flow Diagram.



Dependent variable

The dependent variable for this study was indoor lead dust concentration, which was categorized into two groups: floor and windowsill lead dust concentrations.

For our first study aim, we hypothesized that homes inside the Omaha Lead Superfund site had higher average and median concentrations for both indoor floor and windowsill lead dust. To test this hypothesis, we treated the lead dust concentration as a continuous variable reported in $\mu g/ft^2$. Samples that were below the LOD were replaced with LOD/√2 (Hornung and Reed, 1990). We included homes based on the following eligibility criteria: 1) the participating home was located within the Greater Omaha area and 2) the home had at least one windowsill or floor dust concentration. The final sample size for descriptive analysis was 350 homes.

For our second aim, our working hypothesis was that certain home characteristics, such as older homes, homes inside the Superfund site, and homes with a higher level of soil lead concentration, were associated with elevated indoor lead dust concentrations. Additionally, certain race/ethnicity groups and residents in poverty were more likely exposed to an elevated indoor lead dust concentration. Therefore, we created a new dichotomous variable which categorizes whether a home had an indoor lead dust concentration equal to or higher than the EPA standards of 100 $\mu g/ft^2$ for windowsills lead dust concentration or 10 $\mu g/ft^2$ for floor lead dust concentrations as the dependent variable, and we only included homes in the final logistic models if they had no missing value in any home and occupant characteristics, except for soil lead concentration. The analytic dataset for univariate logistic regression included 313 homes which were with completed measurements on home's and occupant's characteristics and indoor lead dust concentrations. For the final multivariate model, we excluded three homes that were located inside the Omaha Lead Superfund site without soil lead concentrations to maintain reasonable goodness-of-fit of the model.

Independent variables

We initially selected our independent variables if they were available in the digital survey spreadsheet and without more than 50% of missing values. The reasons behind the variable of interest selections were based on either of the following criteria: 1) the selected characteristic was identified as a determinant of elevated lead dust concentration in at least one published study (Jacobs, 1995; Frank, et al., 2019); or 2) the selected characteristic has a considerably plausible association with lead exposure.

The independent variables that were in the final analytic datasets included zip code, whether the house was inside of Omaha Lead Superfund site or not, year house was built, whether the soil in the yard was tested, soil lead concentration, homeownership status, race/ethnicity, annual household income, poverty level, adults' and children's insurance status, whether adults and children had a primary care physician, family size, and numbers of residents under different age groups. Detailed variables categorization and quality control process are presented in Appendix B.

Statistical analysis

We calculated frequencies, percentages, geometric mean, and median for indoor lead dust descriptive statistics. We conducted unpaired t-test and Mann-Whitney test to test our first working hypothesis. For our secondary study aim, we firstly calculated crude odds ratios (ORs) for the association of each covariate with the elevated indoor lead dust concentration. We then entered covariates significantly associated with the outcome in a full multivariate logistic regression model. Through a backward elimination process, we obtained a final partially adjusted model, retaining only covariates that resulted in changes in any remaining parameter estimate greater than 10% to a full model. All analyses used SAS® version 9.4. with a significance level set at two-sided α=0.05.

Results

There were 350 homes eligible for our descriptive analysis. Among these homes, 299 (85.4 %) had windowsill lead dust samples, 338 (96.6 %) had floor lead dust samples, and 287 (82.0%) had both windowsill and floor dust samples collected. More than one-third of homes had a windowsill lead dust concentration (34.8%; geometric mean concentration=1,457.1 µg/ft^2) equal to or higher than the EPA standard for windowsills lead dust concentration of 100 µg/ft^2. About 35.2% homes had a floor lead dust concentration higher than the EPA standard of 10 µg/ft^2. Geometric mean, median and maximum statistics for homes with an elevated lead dust concentration were significantly higher than the EPA standards, with the maximum lead dust concentration reached thousands of times higher (Table 4.1.).

Table 4.1. Residential Indoor Lead Dust Concentration (μg/ft^2) in Omaha, NE.

Characteristics	Windowsill Dust Concentration (n=299)[a]		Floor Dust Concentration (n=338)[b]	
	Lower than the U.S. EPA standard[c]	Equal to or higher than the U.S. EPA standard[c]	Lower than the U.S. EPA standard[d]	Equal to or higher than the U.S. EPA standard[d]
Number (Percentage)	195 (65.2%)	104 (34.8%)	219 (64.8%)	119 (35.2%)
GM (GSD) concentration	<LOD	1,457.1 (7.5)	<LOD	98.5 (6.7)
Median concentration	<LOD	890.0	<LOD	57.0
Maximum concentration	98.0	210,000.0	<LOD	37,000.0

Notes: GM=geometric mean, GSD=geometric standard deviation, μg/ft^2=microgram per square foot, <LOD=under limit of detection.

[a] The detectable level for windowsill lead dust concentration is 60 μg/ft^2.

[b] The detectable level for floor lead dust concentration is 10 μg/ft^2.

[c] The EPA standard for windowsills lead dust concentration is 100 μg/ft^2.

[d] The EPA standard for floor lead dust concentration is 10 μg/ft^2.

Both windowsill (Z-score=3.85, p-value=0.0001) and floor (Z-score=4.58, p-value<0.0001) lead dust concentrations were significantly higher from homes inside of the Omaha Lead Superfund site, compared to homes outside (Table 4.2.). Most of indoor lead dust sampling was conducted within the zip code areas that covered the Omaha Superfund site. The highest sampling zip code area was 68111, with 79 homes that had the indoor lead dust measured and 37 of these homes (46.8%) had an elevated lead dust concentration. There were 9 out of 28 (32.1%) sampling zip code areas had at least 50% of the participated homes with an indoor lead dust concentration failed to meet with the U.S. EPA's lead in dust clearance levels (Figure 4.2).

Table 4.2. Residential Indoor Windowsills and Floor Lead Dust Concentrations (µg/ft^2) Comparisons between Homes Inside and Outside of the Omaha Lead Superfund Site.

Characteristics	Homes Inside of Omaha Superfund Site	Homes Outside of Omaha Superfund Site	Z-score (P-value)
Windowsills Lead Dust[a] (n)	195	104	
Number (%) of elevated lead dust concentration	85 (43.6%)	22 (21.2%)	3.85 (0.0001)
GM of windowsills lead dust concentration (GSD)	200.1 (9.0)	90.7 (5.7)	
Median of windowsills lead dust concentration	<LOD	<LOD	
Floor Lead Dust[b] (n)	219	119	
Number (%) of elevated lead dust concentration	93 (42.5%)	23 (19.3%)	4.58 (<0.0001)
GM of floor lead dust concentration (GSD)	23.3 (6.5)	10.3 (2.9)	
Median of floor lead dust concentration	<LOD	<LOD	

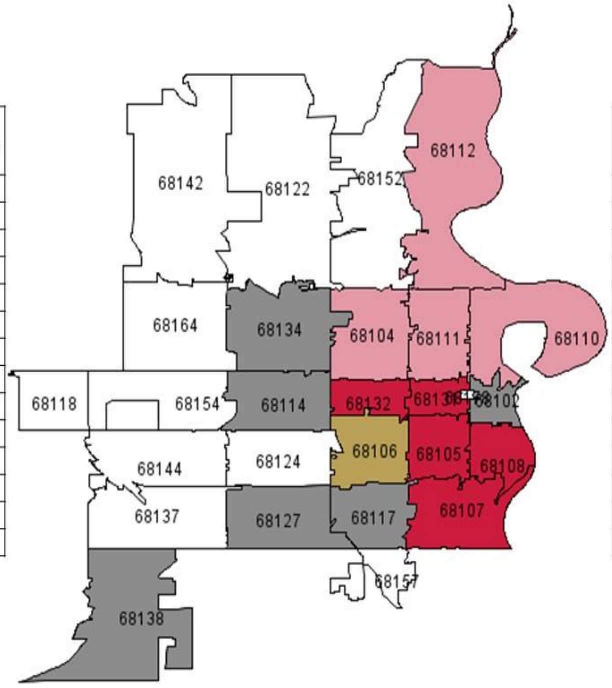
Notes: GM=geometric mean, GSD=geometric standard deviation, µg/ft2=microgram per square foot, <LOD=under limit of detection.

[a] The detectable level for windowsill lead dust concentration is 60 µg/ft^2.

[b] The detectable level for floor lead dust concentration is 10 µg/ft^2.

Figure 4.2. Number of Homes with Indoor Lead Dust sampled and Percentage of Homes with an Indoor Lead Dust Concentration Greater than or Equal to U.S. EPA Clearance Levels of Lead in Dust.

ZIP Code	Number of Homes Sampled (% homes with elevated lead dust)
68127	5 (20.0%)
68128	2 (0.0%)
68131	15 (60.0%)
68132	13 (69.2%)
68134	5 (40.0%)
68137	1 (0.0%)
68138	1 (100.0%)
68142	1 (0.0%)
68144	2 (0.0%)
68147	3 (0.0%)
68152	3 (0.0%)
68154	2 (0.0%)
68157	1 (0.0%)
68164	5 (0.0%)



ZIP Code	Number of Homes Sampled (% homes with elevated lead dust)
68102	1 (100.0%)
68104	38 (34.2%)
68105	27 (74.1%)
68106	19 (21.1%)
68107	44 (56.8%)
68108	24 (70.8%)
68110	20 (40.0%)
68111	79 (46.8%)
68112	22 (50.0%)
68114	8 (12.5%)
68117	4 (75.0%)
68118	1 (0.0%)
68122	1 (0.0%)
68124	3 (0.0%)

Percentage groups
- No home had an elevated indoor lead dust
- Less than 10 homes sampled, but some homes had an elevated indoor lead dust
- 0-25% of homes had an elevated indoor lead dust
- More than 25% but equal to or less than 50% of homes had the elevated indoor lead dust
- More than 50% of homes had an elevated indoor lead dust

Total Number of Homes = 350

Crude and adjusted odds ratio of having an indoor lead dust concentration (either windowsills or floor lead dust) that failed to meet with the U.S. EPA's lead in dust standards are presented in Table 4.3. Houses built before 1950 had the highest crude odds of having indoor lead dust concentration equal to or greater than EPA standard (crude OR=7.31, 95%CI: 2.89, 18.47), and this association persisted even after adjusting for other covariates in the final adjusted model (adjusted OR=6.35, 95%CI: 2.37, 17.02). Soil lead concentration was another significant indicator of elevated indoor lead dust concentration. There were 203 homes in the final sample having a soil lead concentration recorded and most of these homes were inside of the Omaha Superfund site (n=196, 96.6%; results not shown in table). Seventy-eight of these 203 homes had a soil lead concentration equal to or higher than the EPA standard of 400 ppm, which had 4.88 crude odds (95%CI: 2.62, 9.08) of having an indoor lead dust concentration exceeding the EPA standards.

Another 102 homes had a soil lead concentration higher than the California DTSC's standard of 80 ppm and these homes had 2.34 crude odds (95%CI: 1.35, 4.08; results not shown in table) of having an elevated indoor lead dust concentration based on the EPA standards, compared to homes outside of Omaha Lead Superfund site.

Homes within the Omaha Superfund site had almost triple the crude odds (crude OR=2.91, 95%CI: 1.79, 4.72) of having an indoor lead dust concentration exceeding the EPA standards. However, this effect diminished after adjusting for other independent variables (Table 4.3.). Nevertheless, homes were inside of the Omaha Superfund site and with a soil lead level equal to or higher than 400 ppm had both significantly higher crude (crude OR=4.88, 95%CI: 2.62, 9.08) and adjusted (adjusted OR=2.39, 95%CI: 1.13, 5.06) odds of having an indoor lead dust concentration equal to or exceeded the

U.S. EPA's lead in dust standards, compared to house outside of the Omaha Superfund site.

Table 4.3. Prevalence and Odds Ratios of Homes Failing to Meet the U.S. EPA Lead Dust Standards by Home and Occupant Characteristics in Omaha, NE

Characteristics	Indoor lead dust concentration[a]		Odds ratio (95% CI)	
	Fail to meet the EPA standard Number (%)	Meet the EPA standard Number (%)	Univariate model	Multivariate model[b]
<u>Home's Characteristics</u>				
Superfund Site				
No	36 (31.6)	78 (68.4)	Ref.	---
Yes	114 (57.3)	85 (42.7)	2.91 (1.79, 4.72)	---
Year of Home Built				
After 1978	6 (4.0)	28 (17.2)	Ref.	Ref.
1951 to 1978	25 (16.7)	59 (36.2)	1.98 (0.73, 5.36)	2.32 (0.87, 6.90)
1950 and earlier	119 (79.3)	76 (46.6)	7.31 (2.89, 18.47)	6.21 (2.32, 16.63)
Soil Lead Concentration by Superfund Site[c]				
Non-Superfund Site	36 (24.0)	78 (47.9)	Ref.	Ref.
Superfund Site-Low	58 (38.7)	60 (36.8)	2.09 (1.23, 3.58)	1.28 (0.67, 2.43)
Superfund Site-High	54 (36.0)	24 (14.7)	4.88 (2.62, 9.08)	2.45 (1.16, 5.18)
Home Ownership				
Owner-occupied	75 (50.0)	78 (47.9)	Ref.	---
Rental	75 (50.0)	85 (52.1)	0.92 (0.59, 1.43)	---
<u>Occupant's Characteristics</u>				
Race/ethnicity[e]				
White Caucasian	31 (20.7)	56 (34.4)	Ref.	Ref.
Hispanic/Latino	49 (32.7)	48 (29.5)	1.84 (1.02, 3.34)	1.20 (0.59, 2.44)
African American	60 (40.0)	50 (30.7)	2.17 (1.22, 3.86)	2.22 (1.18, 4.18)
Other	9 (5.5)	10 (6.7)	2.01 (0.74, 5.47)	1.81 (0.61, 5.37)

Table 4.3. (continued). Prevalence and Odds Ratios of Homes Failing to Meet the U.S. EPA Lead Dust Standards by Home and Occupant Characteristics in Omaha, NE

Characteristics	Indoor lead dust concentration[a]		Odds ratio (95% CI)	
	Fail to meet the EPA standard Number (%)	Meet the EPA standard Number (%)	Univariate model	Multivariate model[b]
Poverty Level[f]				
None (FPL≥125)	44 (29.3)	58 (35.6)	Ref.	---
Relative (100<FPL<125)	27 (18.0)	27 (16.6)	1.32 (0.68, 2.56)	---
Moderate (50≤FPL≤100)	60 (40.0)	55 (33.7)	1.44 (0.84, 2.46)	---
Extreme (FPL<50)	19 (12.7)	23 (14.1)	1.09 (0.53, 2.24)	---
Health insurance for child				
Yes	133 (88.7)	148 (90.8)	Ref.	---
No	4 (2.7)	2 (1.2)	2.25 (0.40, 12.35)	---
No child in house	13 (8.0)	13 (8.7)	1.11 (0.50, 2.47)	---
Primary care physician for child				
Yes	131 (87.3)	146 (89.6)	Ref.	---
No	6 (4.0)	4 (2.4)	1.67 (0.46, 6.06)	---
No child in house	13 (8.7)	13 (8.0)	1.12 (0.50, 2.49)	---
Health insurance for adult				
Yes	98 (65.3)	126 (77.3)	Ref.	Ref.
No	52 (34.7)	37 (22.7)	1.81 (1.10, 2.97)	1.90 (1.04, 3.46)
Primary care physician for adult				
Yes	98 (65.3)	127 (77.9)	Ref.	---
No	52 (34.7)	36 (22.1)	1.87 (1.14, 3.09)	---

Notes: OR=odds ratio, CI=confidence interval, Ref.=reference group.

[a] The U.S. EPA standards for windowsills and floor lead dust concentrations are 100 $\mu g/ft^2$ and10 $\mu g/ft^2$, respectively.

[b] Total sample of the multivariate model is 310 homes. Each variable is adjusted for all other available variables listed in the column.

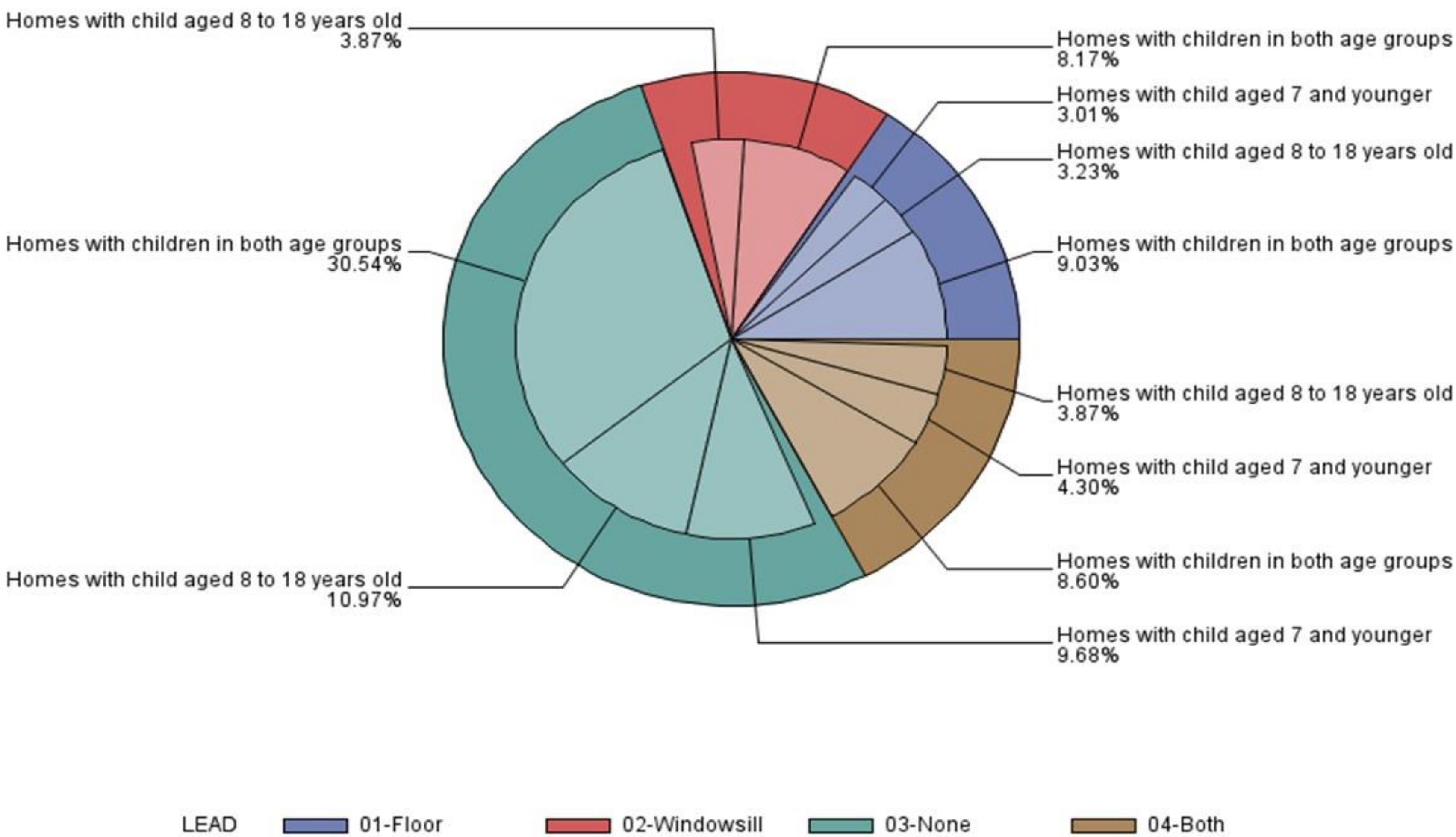
[c] Three homes inside of the Superfund site without soil lead concentration results were excluded; Low=soil lead concentration was lower than 400 ppm; High=soil lead concentration was equal to or higher than 400 ppm.
[d] Both White Caucasians and African Americans were non-Hispanic; Other race/ethnicity included Asian, American Indian, Native Hawaiian/other Pacific Islander, and multiple races.
[e] FPL=Federal Poverty Level, which was calculated by using the participated home’s annual household income, numbers of children and adult occupants, and 2017 U.S. Census Bureau’s Poverty Thresholds.

We found that participants who self-identified as non-Hispanic African American (crude OR=2.17, 95%CI: 1.22, 3.86) and Latino/Hispanic (crude OR=1.84, 95%CI: 1.02, 3.34) had higher crude odds of elevated indoor lead dust exposure, compared to participants who were White Caucasians. However, after adjusting home characteristics and other occupant characteristics, only non-Hispanic African American group maintained a significant adjusted odds ratio of 2.32 (95%CI: 1.23, 4.35). We found no association between elevated indoor lead dust concentration with children's insurance and primary care physician status in either crude or adjusted analyses, but both adult's insurance (crude OR=1.81, 95%CI: 1.10, 2.97) and primary care physician status (crude OR=1.87, 95%CI: 1.14, 3.09) were associated in the univariate analysis. Furthermore, homes with adults not covered by any type of insurance had nearly double the adjusted odds (adjusted OR=1.91, 95%CI: 1.05, 3.49) of having an elevated indoor lead dust concentration.

Poverty level was not directly associated with indoor lead dust concentration (Table 4.3). However, a household with an extreme poverty level (FPL<50) had higher crude odds ratio (crude OR=2.40, 95%CI: 1.11, 5.21) of living in a home within the Omaha Superfund site, compared to households above the poverty level (results not shown in table). Similar relationship (crude OR=2.20, 95%CI: 1.26, 3.83) also shown among households with a moderate poverty status (50≤FPL≤100). The positive association found between poverty and Superfund site homes indicated that there is a potential indirect effect of poverty on elevated indoor lead dust concentration.

Among 313 homes with all characteristics recorded, 287 (91.7%) were with at least one child aged 18 years or younger, and 219 (70.0%) were with at least one child aged seven years or younger. Figure 4.3 presented the distribution of indoor lead dust status among homes with different age groups of children. Indoor lead dust status was categorized into four different categories: 01-homes with elevated floor lead dust concentration only (blue); 02-homes with elevated windowsill lead dust concentration only (red); 03-homes without elevated floor or windowsill lead concentrations; and 04-homes with both floor and windowsill lead concentrations exceeded the EPA standards (brown). The internal slices represented homes with different age groups of children. There were also four categories of homes: 1) homes with no child; 2) homes with children aged seven and younger only; 3) homes with children aged 8 to 18 only; and 4) homes with children in both of the previous two categories. About 8.6% of homes had children in both seven and younger, and 8 to 18 age groups had elevated lead dust concentrations from floor and windowsill samples (Figure 4.3). There were 103 (32.9%) homes with at least one child aged seven years or younger exposed to at least one higher floor or windowsill lead, with 40 of these homes had both floor and windowsill lead dust concentrations exceeded the EPA standards. It is worth noting that of the 31 out of those 40 homes that had both floor and windowsill lead dust concentrations above the EPA standards all were at the poverty level, including four homes were extremely poor, seventeen were moderately poor, and ten were considered relatively poor.

Figure 4.3. Percentage of Homes with Different Age Groups of Children and Their Indoor Lead Dust Status.



Discussion

Descriptive indoor lead dust concentrations found in this study showed that indoor lead dust hazards are still prevalent among homes in the Greater Omaha area. About 34.8% of homes in this study had a windowsill lead dust concentration exceeded the EPA standard, and 35.2% of homes had a floor lead dust concentration that exceeded the EPA standard. These numbers were lower than our preliminary findings (about 50%) among homes with a zip code where the Omaha Superfund site is located (Qin and Achutan, 2021), because of larger sample size and clearer identification of homes' information. However, these percentages (34.8% and 35.2%) were still higher than the national estimates of 16% of housing units that having one or more lead dust hazards on either floors or windowsills (Jacobs et al., 2002). Moreover, higher percentages (about 43%) of homes within the Omaha Superfund site had one or more elevated floors and windowsills' lead dust concentrations. These findings suggested that there are potential rooms for improvement in lead prevention and cleaning in Omaha residents' homes.

We found that higher indoor dust concentration was most common in houses built before 1978, especially those were built before 1950. This finding was consistent with previous studies (Jacobs 1995; von Lindern, Spalinger, Bero et al., 2003; Raymond et al., 2011; Frank et al., 2019; Yeter et al., 2020). Most of homes (62.3%) in this study were built before 1950 which was very similar to the statistics of housing built prior to 1950 within the Omaha Superfund site. Previous national housing studies found that dust lead hazards were more likely presented in homes with deteriorated indoor lead-based paint, and recommended demolition, remodeling, and renovation to reduce lead exposure within housing units with lead-based paint (Jacobs et al., 2002). Results showed that, although demolition, remodeling, and renovation activities may increase lead exposures over a short period of time, they reduce the exposure significantly over the long run (Jacobs et al., 2002). Another effective way to permanently eliminate lead exposure in these housing units is to conduct soil lead abatement and paint stabilization (Jacobs et al., 2002; U.S. EPA, 2020d). However, the usual cost of soil lead abatement and paint stabilization is high so that support or orders from state and local health departments and governments are required. Otherwise, it is less likely that residential lead exposure will be reduced or eliminated in a timely manner.

House perimeter soil lead concentration has been identified as an important contributor to home's indoor lead dust concentration (Adgate et al., 1995; von Lindern, Spalinger, Bero et al., 2003; Clark et al., 2004). Specifically, for houses that had soil remediation, interior lead dust levels were significantly reduced (Clark et al., 2004). In this dataset, the sampling time of soil and dust lead measurements at each household was in irregular calendar years. Therefore, we are not able to determine the temporal association between soil lead remediation results and indoor lead dust concentrations. Nevertheless, our current findings still suggests that high level of house perimeter soil lead was associated with elevated indoor lead dust concentration. Although homes inside of the Superfund site had no significant adjusted odds of having an elevated indoor lead dust concentration, we found homes inside of the Superfund site with a soil lead level higher than the EPA standard had 2.39 higher odds of having an elevated indoor lead dust concentration, compared to non-Superfund site homes. Among all non-Superfund site homes, there were seven homes that had their soil tested and only one of them had a soil concentration that failed to meet with the EPA standard of 400 ppm. However, six of these seven non-Superfund site homes had an elevated indoor lead dust concentration. To better understand the relationship between house perimeter soil lead concentration and indoor lead dust concentration in Omaha, future studies should consider a pre-post study design to measure soil and dust lead exposure among both Superfund and non-Superfund homes.

Studies showed that African American children often have the highest national average BLL compared to non-Hispanic White Caucasian and Latino/Hispanic children (Yeter et al., 2020; Pirkle et al., 1994, Wheeler and Brown, 2013; White et al., 2016). Household lead dust contamination is one of the greatest contributors to elevated BLL among African American children (Yeter et al., 2020; Raymond et al., 2011). In this study, we found that not only African American but also Latino/Hispanic residents were more likely to be exposed to higher lead dust concentration in their own homes. Although the significant crude association between Latino/Hispanic group and higher indoor lead dust concentration diminished after adjusting for other characteristics, it is crucial that future research and lead prevention and managements will focus on these racial and ethnicity minority groups. Furthermore, it is worth noting that other racial and ethnicity minority groups (Asian, American Indian, Native Hawaiian/other pacific islanders, and multiple races) had higher odds of being exposed to elevated indoor lead dust concentration, even though this is not significant. Per capita, Omaha is one of the leading cities where refugees resettle, and most of these refugees are from Asian countries like Myanmar and Bhutan (Ahmed and Gelman, 2021). Due to the limited data on the racial and ethnicity minority groups, we were not able to clearly understand the indoor lead dust exposure status among these groups, especially for refugees. Therefore, we would like to strongly encourage local organizations and community partners to closely examine indoor lead exposure for children of refugee families in the future Omaha lead studies. This will enable us to better address the environmental justice issues in the Greater Omaha area.

Poverty, as a main indicator of socioeconomic status, was identified as both direct and indirect risk factors of high children's BLL and exposure to lead hazards (Bellinger 2008; Kim et al., 2018). The current study demonstrated no direct association between poverty and indoor lead dust concentration. However, we found participants living at poverty levels were more likely to live in the Omaha Superfund site. Most of these families with a child and had both floor and windowsill's lead concentrations exceeded the EPA standards were in poverty. Due to the limitation and uniqueness of our data, we were not able to further examine potential indirect or mediator-moderator effects of poverty on indoor lead dust concentration. We recommend future studies to use a longitudinal design to collect both indoor lead dust concentration and occupant's socioeconomic characteristics, and therefore to better examine the effect of socioeconomic status on indoor lead dust concentration.

There are several limitations to this study. First, some characteristics we used in our analytical models were provided by a self-reported survey, which is subject to recall bias. Second, the cross-sectional design could not identify any temporal association between our variables of interest. Third, limited variables and one-time lead measurements at each household restrict our opportunities to utilize advanced statistical model to better understand the relationship between occupant's characteristics with indoor lead dust concentration. Fourth, the results may not be generalizable to other Superfund sites or cities in the United States, because the original in-home lead assessment project carried out by OHKA mainly focused on housing in the Greater Omaha area, with a specific focus on the Omaha Superfund site.

Conclusion

Lead dust hazard is prevalent in Omaha and thus remains a public health concern. Homes inside the Omaha Lead Superfund site are more likely to have an elevated indoor lead dust concentration because of historical lead pollution, high soil concentration, as well as use of lead-based paint in the housing units before 1950. Findings from this study suggest that there exists a significant portion of the population who are exposed to high levels of lead at home, which pose serious health and neurodevelopmental risks for children, and that continuous efforts in effective environmental hazards control and lead poisoning prevention programs are critically needed in Omaha. Future research should consider a longitudinal study design to consistently provide lead exposure knowledge to the community, to better address the lead poisoning challenge and children's environmental health justice.

CHAPTER 5: BLOOD LEAD LEVELS OF CHILDREN ADMITTED TO HOSPITALS AND CLINICS IN OMAHA, NE

Abstract

Background: Reducing blood lead levels (BLL) in children is essential to their healthy development. Although research and reports suggested the incidence of elevated BLL in Omaha children is reducing, a gap exists for most Omaha children receiving blood lead tests. This study aimed to determine the prevalence of children with elevated BLL (≥5 micrograms per deciliter [μg/dL]) among hospital-admitted children who had blood tests. Additionally, we aimed to characterize the primary diagnoses of children who had an elevated blood lead level. Methods: We performed analyses on electronic health record data that included all children aged 18 and younger who had at least one valid blood lead test result. We conducted logistic regression and generalized estimating equation models to determine the association between elevated BLLs and children's demographic characteristics. Results: Approximately 3.2% of children who had their blood lead tested in a hospital or clinic in the Greater Omaha area had a BLL equal to or higher than five μg/dL. A higher percentage of tests outside of the Greater Omaha area had elevated BLLs. In the Greater Omaha area, females were less likely to have an elevated BLL than males (adjusted OR=0.56, 95%CI: 0.34, 0.93). More than 60% of the blood lead tests were conducted for health screening purposes. Conclusion: Omaha children's BLL has decreased compared to the early 1990s. However, our findings from electronic health data showed a higher percentage of children had elevated BLL compared to national level data, suggesting childhood elevated BLL may still be a problem in Omaha, NE.

Keywords: blood lead level, childhood lead poisoning, electronic health record, lead screening.

Introduction

Lead is known to cause multiple adverse health problems in children. No blood lead level (BLL) is known to be safe for children (Bellinger, 2008; CDC, 2012; AAP, 2016). BLLs greater than 80 microgram per deciliter (µg/dL) can cause adverse effects in children including coma, convulsions, brain damage, and even death (Drasch et al., 1988; Woolf et al., 2007; AAP, 2016). Symptoms such as stomach pain, poor appetite, and irritability are common among children who have BLLs in the moderate range of around 20 µg/dl (AAP, 2016). Research findings have consistently documented association between even lower levels of blood lead (less than 5 or 10 µg/dL) and children's neurobehavioral disorders (Nigg et al., 2010; Braun et al., 2018), as well as academic performance (Miranda et al., 2007; Chandramouli et al., 2009; McLaine et al., 2013; Shadbegian et al., 2019). Currently, no treatment has been recognized as effective in fully correcting lead poisoning's adverse health effects and outcomes in children (AAP, 2016). Once onset, childhood lead-related health damage may persist into adulthood (AAP, 2016; Reuben et al., 2017).

Historically, one of the most effective methods to protect children from lead-related adverse health effects was to monitor and reduce their exposures to lead based on values deemed protective according to clinical recommendations and or regulatory levels. During the mid-20th century, a BLL of 80 µg/dl was believed to be protective enough for lead poisoning (Hernberg, 2000) and the clinical definition of lead poisoning BLL was set at 60 µg/dl (Graef et al., 1971). In 1971, the U.S. Surgeon General's report defined a BLL of 40 µg/dl as considered evidence of "undue absorption of lead, either past or present". Additionally, a person who had a BLL of 40 µg/dl, with another two previous consecutive blood lead tests showed BLLs of 80 µg/dl or higher with or without symptoms, would be confirmed as "lead poisoning" (Steinfeld, 1971). The U.S. CDC officially took the leadership role in defining BLL and the criterion for interpreting BLL among children in 1978, including defining the term of “elevated blood lead level” and confirming that a BLL of 30 μg/dl or higher would be defined as “increased lead absorption and lead poisoning in young children” (CDC, 1978). Between 1978 and 1991, the criterion for “lead poisoning in young children” was revised three times because of new clinical and scientific evidence appeared, and the value of “elevated blood lead level” was also reduced from 30 μg/dl to 10 μg/dl on the basis of improved laboratory techniques for measuring blood lead (CDC, 1978; 1985; 1991). In 1991, terminology to describe lead poisoning in young children was updated again with the term “elevated blood lead level” changed to a “blood lead level of concern”, and the new threshold value of 10 μg/dl was used in prompting state and local health departments’ efforts in managing and monitoring lead poisoning cases (CDC, 1991; Ettinger et al., 2019). In 2012, CDC adopted the term “blood lead reference value”, replacing the previous “blood lead level of concern” and lowered the value to 5 μg/dl to focus on primary prevention of lead exposure. The blood lead reference value was determined by the 97.5th percentile of children's BLL distribution from the latest two National Health and Nutrition Examination Surveys (NHANES) and would be updated every four years. The CDC’s methods in determining BLLT was a breakthrough in the hazardous chemical regulatory history as it not only characterized individual blood lead level test results but also compared the results to the population estimates.

Since 1976, the NHANES has estimated lead exposures for both adults and children by measuring BLLs. Results in the 1970s indicated approximately 88% of U.S. children who were younger than six years old had a BLL ≥10 μg/dL (Lanphear, 2005). Analyses of NHANES BLL data from 1990’s showed that BLL in U.S. children younger than six years old have significantly decreased (Pirkle et al., 1994; Raymond et al., 2014; Egan et al., 2021). Reasons for BLL declines between the 1970s and 1990s included a series of federal regulations, such as banning lead-based paint and leaded gasoline and the application of the Comprehensive Environmental Response, Contamination and Liability Act of 1980 (CERCLA) known as the Superfund program. A hazardous site deemed to affect human health and the environment would be determined as a Superfund site by the U.S. EPA. The Superfund program allotted funds for the application of hazardous resources cleanup and removal practices resulting from historical environmental contamination of lead and other harmful waste byproducts. Records have demonstrated that cities and areas classified as Superfund sites contaminated by lead often coincided with problems of childhood lead poisoning (Farrell et al., 1998; von Lindern, Spalinger, Petroysan et al., 2003). The Omaha Lead Superfund site is one of the largest residential Superfund sites in the U.S. where childhood lead poisoning has been a serious public health problem. In the early 1990s, over 25% of the children between 0-5 years who lived in Douglas County (of which Omaha is the county seat) had BLL greater than 10 µg/dl (U.S. EPA, 2021d). Similar to the national trends of BLL decline, the research and surveillance data focused on Omaha also indicated that BLLs in Omaha children have generally decreased in the past decade (NE DHHS, n.d.; Klemick, el al., 2020; McClure, et al., 2016). However, the available data only included a limited number of young children living in the Omaha area. Most children living in the Omaha area, especially those living in the Omaha Lead Superfund site, did not receive BLL tests. Additionally, children living in Omaha are still exposed to persistent environmental lead sources, such as deteriorated lead-based paint and dust in older housing and lead contaminated soil. Therefore, there is a need of continuous investigation of BLL status in children, living in Omaha.

While NHANES and CDC blood lead surveillance data provides a comprehensive range of participants' characteristics, most of U.S. children's BLL studies have focused on children aged 1-5 years with certain sociodemographic characteristics over a selected period of time. Only a handful of studies have investigated the distribution of BLLs in U.S. children older than 5 years of age with multiple sociodemographic characteristics or environmental lead exposure information (Benson et al., 2016; Egan et al., 2021). In addition, there is a lack of research regarding children who visited a clinic or were admitted to a hospital due to potential lead poisoning. Electronic health records (EHR) can provide valuable information, such as diagnosis and comorbidities, to further our understanding on the prevalence of childhood lead poisoning in the Omaha community. The aim of this study was to determine the prevalence of children with elevated BLL (≥5 μg/dL) among hospital admitted children who had blood tests in Omaha, Nebraska. Additionally, we aimed to characterize the primary diagnoses of children who had an elevated blood lead level.

Methods

Study design and data source

The study design was a cross-sectional study with secondary data analysis. The data of this study was encounter-level EHR that included all children outpatients and inpatients who were aged 18 years old or younger when admitted to a hospital or a clinic in the Nebraska Medicine system between 2014 and 2019. Before we received the data, all direct (e.g., name, date of birth, medical record number, address, zip code, etc.) or indirect (e.g., admission date, discharge date, etc.) identifiers linking the data to the individual subjects were removed by the Nebraska Medicine Electronic Health Record Access Core Office. The University of Nebraska Medical Center's institutional review board approved this study before its inception. All EHR data for this study were deidentified. We included all children patients who had at least one valid blood lead test done irrespective of their visit type in our analyses.

Study variables

The primary dependent variable of this study was the patient's BLL measured by μg/dL. A dichotomous variable that determined if a child had a BLL equal to or higher than the CDC reference value of 5 μg/dL was created.

Independent variables included age, gender, race, insurance type, location, and primary diagnosis. Age was determined at the time the patient received the blood lead test. Race was categorized as White Caucasian, African American, other (included Asian, American Indian, Alaska native, Hispanic, Native Hawaiian/Pacific Islander, multiracial, and other), or unknown (included patient refused and unknown). Insurance type was categorized as private, Medicaid, and self-pay. Location was determined by the location of the hospital and clinic where the blood lead test was carried out. There were two categories of location: The Greater Omaha area and the rest of Nebraska. The Greater Omaha area included 20 hospitals and clinics in the Greater Omaha urban area. There were 13 hospitals and clinics located in the rest of Nebraska, and most of them were in rural area. Primary diagnosis was determined by the ICD-10 code of patient's primary diagnosis, which was categorized as outpatient encounters, diseases of body systems, screening for factors other than lead that influencing health status, child health screening, suspected exposure to lead, and abnormal blood lead level. Encounters and patients with missing information for at least one of the independent variables were excluded from the analysis.

Statistical Analysis

We described children's BLL for two different location groups by different BLL groups at both patient level and encounter level. For patient level data, we only included the first ever hospital or clinic visit's information. We then evaluated the association between children's BLL and independent demographic variables (age, gender, race, and insurance type) in univariate and multivariate logistic regression models stratified by location groups. We also measured the association between dependent and independent variables by conducting sensitivity tests. We conducted marginal and random-effects models to account for multiple blood lead tests that one child received, we conducted sensitivity tests by using generalized estimating equation (GEE) approach. All analyses used SAS® version 9.4 (SAS Institute Inc., Cary, NC) with a two-sided significance level set at $\alpha=0.05$.

Results

A total of 4,388 blood lead tests were performed on 3,918 children aged 0 to18 years of age in Nebraska between 2014 and 2019. Descriptive statistics indicated about 93% of the blood tests had an BLL less than the BLL reference of 5 μg/dL across the state of Nebraska. Omaha, the largest metropolitan city in Nebraska carried out a total of 2,404 blood lead tests for 2,134 children who were admitted to a hospital or a clinic in the Greater Omaha area during this period based on the Nebraska Medicine EHR records. There were 190 children visited hospitals or clinics in the Greater Omaha area had more than one blood lead test between 2014 and 2019. These records indicated 69 children in the Greater Omaha area (3.2%) contributed approximately 6.1% of blood lead tests showed a BLL equal to or higher than the CDC reference level of 5 μg/dL. While there were a smaller number of blood lead tests (1,984) and children tested (1,784) outside the Omaha area, a similar percentage (3.1%) of children contributed to a higher percentage (8.3%) of blood lead tests that failed to meet the CDC reference BLL of 5 μg/dL (Table 5.1). The majority of blood lead tests were administered for the age group younger than six years old. The percentages were 93.7% for the Greater Omaha area and 98.2% for the rest of Nebraska, respectively. Only a small proportion (<5%) of blood lead tests were conducted for the children aged 6 to 11 years and the children older than 11 years old. However, children aged between 6 to 11 years old had the highest percentage of elevated BLLs among all three age groups. Specifically, in the Greater Omaha area, 6 out of 90 children (6.7%) aged 6 to 11 years old had an initial BLL ≥ 5 μg/dL. In total, 15% of the blood lead tests administered for children aged 6 to 11 years old had a BLL ≥ 5 μg/dL, and 8.9% of the tests had a BLL ≥ 10 μg/dL. The majority of the blood lead tests with elevated values were within the concentration group of 5 to 10 μg/dL, but there were still children who had a BLL over 40 μg/dL. Children's BLL ranged from below the limit of detection to 67.2 μg/dL for the Omaha area, and from below the limit of detection to beyond the limit of detection at 65 μg/dL for the rest of Nebraska (data not shown in table).

Table 5.1. Blood Lead Levels (µg/dL) among Nebraska Children Who Received a Blood Lead Test during Visits to Hospitals and Clinics, 2014-2019.

	Greater Omaha Area			Rest of Nebraska		
	Total number of children=2,134 Number of children (%)			**Total number of children=1,784** Number of children (%)		
Age group	Age < 6	Age 6 to 11	Age > 11	Age < 6	Age 6 to 11	Age > 11
Number of children	2,007 (94.05)	90 (4.22)	37 (1.73)	1,751 (98.15)	27 (1.51)	6 (0.34)
Number of children with a confirmed initial BLL equal or higher than 5 µg/dL by BLL Group						
5≤ BLL <10 µg/dL	48 (2.24)	4 (0.19)	1 (0.05)	40 (2.24)	1 (0.06)	2 (0.11)
10≤ BLL <20 µg/dL	10 (0.47)	1 (0.05)	0 (0.00)	12 (0.67)	0 (0.00)	0 (0.00)
20≤ BLL <30 µg/dL	2 (0.09)	1 (0.05)	0 (0.00)	1 (0.06)	0 (0.00)	0 (0.00)
BLL ≥30 µg/dL	2 (0.09)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Total no. of children had an elevated BLL	62 (2.91)	6 (0.28)	1 (0.05)	53 (2.97)	1 (0.06)	2 (0.11)
	Total number of tests=2,404 Number of tests (%)			**Total number of tests=1,984** Number of tests (%)		
Age group	Age < 6	Age 6 to 11	Age > 11	Age < 6	Age 6 to 11	Age > 11
Number of tests	2,253 (93.72)	113 (4.70)	38 (1.58)	1,948 (98.19)	30 (1.51)	6 (0.30)
Number of tests with confirmed BLLs equal or higher than 5 µg/dL by BLL Group						
5≤ BLL <10 µg/dL	99 (4.12)	7 (0.29)	1 (0.04)	118 (5.95)	3 (0.15)	2 (0.10)
10≤ BLL <20 µg/dL	22 (0.92)	8 (0.33)	0 (0.00)	37 (1.86)	1 (0.05)	0 (0.00)
20≤ BLL <30 µg/dL	7 (0.29)	2 (0.08)	0 (0.00)	2 (0.10)	0 (0.00)	0 (0.00)
BLL ≥30 µg/dL	3 (0.12)	0 (0.00)	0 (0.00)	2 (0.10)	0 (0.00)	0 (0.00)
Total no. of tests with an elevated BLL	129 (5.37)	17 (0.71)	1 (0.04)	160 (8.06)	4 (0.20)	2 (0.10)

Notes: BLL=blood lead level; µg/dL=microgram per deciliter.

Table 5.2. presented the distribution of children's blood lead tests by the individual level of demographic characteristics. Although most blood lead tests were administered for children less than six years old, children aged six and older had the higher percentage of elevated BLLs in both the Greater Omaha area (5.5%) and the rest of Nebraska (9.1%). However, children aged six and older did not have significantly higher odds of experiencing elevated BLLs than those younger than six.

The number of blood lead tests for males (1,110, 52%) and females (1,024, 48%) were close in the Greater Omaha area, and the ratio was similar in the rest of Nebraska (males: 914, 51% vs. females: 870, 49%). In the Greater Omaha Area, elevated BLLs were less common among females than males in crude and adjusted analyses. In the rest of Nebraska, there was no significant association between gender and elevated BLLs (Table 5.2.).

More than 72% of the children were covered by private insurance (74% in the Greater Omaha area and 72% in the rest of Nebraska). The percentage of children with Medicaid coverage was 21% in the Greater Omaha area and 15% in the rest of Nebraska, respectively. Children who visited hospitals or clinics outside of the Greater Omaha area and were without insurance when blood lead test was conducted had both crude and adjusted odds ratios of elevated BLL higher than children with private insurance coverage (Table 5.2). This association was also confirmed by the GEE models (Appendix C).

Different distributions of blood lead tests were administered to different race/ethnicity groups in the Greater Omaha area and the rest of Nebraska. In the Greater Omaha area, African American children were the leading race/ethnicity group (47%) that received blood lead tests. While in the rest of Nebraska, most of the blood lead tests were conducted for White Caucasian children (87%). We found no association between race/ethnicity group and elevated BLLs in either crude or adjusted logistic regressions.

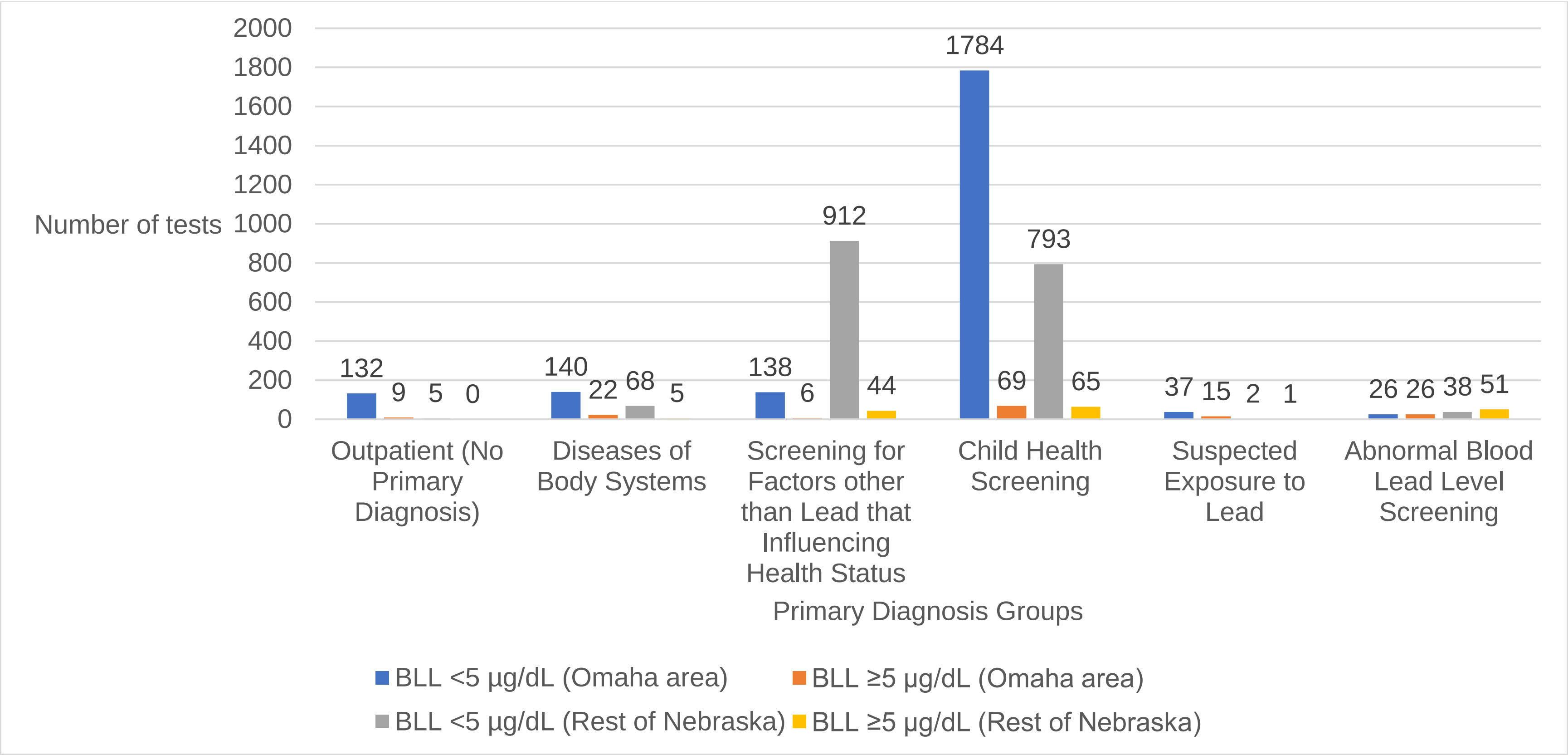
Table 5.2. Frequency of Individual Demographics and Odds Ratios of Having an Elevated Blood Lead Level for Children Who Received a Blood Lead Test during Visits to Hospitals and Clinics in Nebraska, 2014-2019.

Characteristics	Greater Omaha Area (number of children=2,134)			Rest of Nebraska (number of children=1,784)		
	BLL≥5 μg/dL	Odds ratio (95%)		BLL≥5 μg/dL	Odds ratio (95%)	
	Number (%)	Univariate model	Multivariate model[a]	Number (%)	Univariate model	Multivariate model[a]
Age group						
Less than 6	62 (3.1)	Ref.	Ref.	53 (3.0)	Ref.	Ref.
Aged 6 and older	7 (5.5)	1.83 (0.82, 4.09)	1.77 (0.78, 4.01)	3 (9.1)	3.20 (0.95, 10.83)	2.85 (0.80, 10.13)
Gender						
Male	45 (4.1)	Ref.	Ref.	33 (3.6)	Ref.	Ref.
Female	24 (2.3)	0.57 (0.34, 0.94)	0.56 (0.34, 0.93)	23 (2.6)	0.73 (0.42, 1.25)	0.74 (0.43, 1.28)
Insurance						
Private	44 (2.9)	Ref.	Ref.	38 (2.8)	Ref.	Ref.
Medicaid	16 (4.9)	1.73 (0.96, 3.10)	1.71 (0.95, 3.09)	11 (2.9)	1.03 (0.52, 2.04)	1.07 (0.54, 2.12)
Self-pay	9 (3.4)	1.18 (0.57, 2.45)	1.07 (0.50, 2.27)	7 (9.9)	3.74 (1.61, 8.70)	3.56 (1.49, 8.50)
Race[b]						
White Caucasian	25 (3.2)	Ref.	Ref.	51 (3.3)	Ref.	Ref.
African American	33 (3.3)	1.04 (0.61, 1.76)	1.01 (0.59, 1.73)	1 (3.2)	0.98 (0.13, 7.30)	0.75 (0.10, 5.91)
Other	8 (2.8)	0.87 (0.39, 1.96)	0.81 (0.36, 1.83)	2 (1.7)	0.50 (0.12, 2.07)	0.40 (0.09, 1.73)
Unknown	3 (5.5)	1.76 (0.52, 6.03)	1.72 (0.49, 6.01)	2 (2.3)	0.68 (0.16, 2.85)	0.65 (0.15, 2.72)

Notes: BLL=blood lead level; μg/dL=microgram per deciliter; OR=odds ratio, CI=confidence interval, Ref.=reference group.
[a] Each variable is adjusted for all other variables in the table.
[b] Other race/ethnicity included Asian, Hispanic, American Indian, Alaska Native, Native Hawaiian/Pacific Islander, multiracial, and other. Unknown included patient refused to answer and unknown.

Among 4,388 blood lead tests, most of the tests were made for the purpose of health screening. The most common reason for blood lead tests was routine health examinations for young children (2,711, 61.8%). About 4.9% of health screening blood lead tests found an elevated BLL (Figure 5.1). There were 235 blood lead tests (5.4%) conducted because of onset of diseases and 1,100 tests (25.1%) were conducted because the children were diagnosed with adverse health effects. Only 55 tests were conducted because of suspected exposure to lead, and most of these tests were made in the Greater Omaha area's hospitals and clinics. Patients who had a history of elevated BLL or had an abnormal blood lead level during the visit were categorized for abnormal blood lead level screening. More than 50% of the blood lead test for this primary diagnosis group showed an elevated BLL.

Figure 5.1. Number of Children's Blood Lead Tests by Primary Diagnosis Groups, Stratified by the Greater Omaha Area and Rest of Nebraska, 2014-2019.



Notes: BLL=blood lead level; µg/dL=microgram per deciliter.

Discussion

In general, the cases of elevated BLL in Omaha children have decreased over the past 30 years. Although data from this study only represented a proportion of Omaha children who had blood lead tests between 2014 and 2019, the percentage of elevated BLL cases (BLL≥ 5 μg/dL, 5.7%; BLL ≥ 10 μg/dL, 1.8%) was lower than historical 1990s data (25% of tested children had a BLL ≥ 10 μg/dL). Findings from this study indicated that childhood BLL are still elevated and a health concern in Omaha. The U.S. CDC childhood blood lead level surveillance program reported 2.0% of children younger than six years old had BLL ≥5 μg/dL in 2019 (CDC, 2019), and the 2011-2016 NHANES data estimated 1.3% (95%CI: 0.7, 2.4) and 0.5% (95%CI: 0.1, 0.5) population prevalence of BLLs ≥5 μg/dL for children aged 1 to 5 years old and age 6 to 11 years old, respectively (Egan et al., 2021). Percentages of elevated BLL cases for both age groups were higher in our Omaha study population compared to the CDC and NHANES data.

Previous studies indicated that children in urban area groups often had higher mean BLL compared to children living in the rural area (Angle et al., 1984; Aelion and Davis, 2019) because urban areas have more potential environmental lead exposure such as legacy-leaded gasoline from traffic (Mielke et al., 1997; Mielke and Zahran, 2012; Mielke et al., 2011) and older homes that contained lead-based paint (Rasmussen et al., 2013; Bell et al., 2010). In this study, a higher percentage of blood lead tests was with an elevated BLLs in other areas of Nebraska compared to the Greater Omaha area. The other areas in this study included North Platte City, Hastings, and Grand islands, commonly recognized as rural areas in the Nebraska. It is possible that this because most of Omaha's children remained untested, while a significant proportion of children who lived in the rural area were tested. For example, according to U.S. Census, about 5,600 children under 18 years of age live in North Platte City, NE (U.S. Census Bureau, 2019), and in this study we had 1,400 children who received at least one blood lead test in the North Platte City's hospitals and clinics. This finding suggested that childhood lead poisoning may be underestimated and a public health problem in rural Nebraska. In the 2015 NE DHHS blood lead levels report, only 32 children from Lincoln County (where North Platte City is located) had their blood lead level tested (NE DHHS, n.d.). The local and state health departments should consider increasing blood lead level screening and monitoring in the rural area.

The previous chapter on residential lead dust suggested that African American children may be exposed to elevated environmental lead dust and thus made them more likely to have higher BLLs than White Caucasian children. A similar suggestion was made based on NHANES BLL data (Pirkle et al., 1994; Aelion and Davis, 2019). In this study, we did not find significant differences in BLLs among different racial groups. It is possible that EHR data may not be able to capture minority racial groups, especially those with lower social-economic status. It is worth noting that Hispanics, one of the most populated minority groups in the Omaha area, only had six children who had their blood lead tested in a hospital or a clinic. Future studies should investigate the prevalence and accessibility of children's blood lead tests among racial minority groups.

In this study, we found that males had higher odds of having elevated BLLs compared to females in the Greater Omaha area, but data from the rest of Nebraska showed no statistically significant difference between the BLLs of males and females. Results of BLL by gender have been contradictory in the previous studies. For example, some researchers reported that more males had elevated BLLs than females (Vivier et al., 2011; McClure et al., 2016). Other studies found that females were more likely to have higher BLLs. Aelion and Davis found that females’ average BLL was higher than the males’ in South Carolina (Aelion and Davis, 2019), and Wheeler and Brown reported that a greater percentage of female had BLL ≥5 μg/dL than males (Wheeler and Brown, 2013). We had inconsistent findings on BLLs of different gender groups within our study. Future studies on gender differences in BLL may focus on gender differences in behavior and metabolism and examine potential environmental lead exposure.

Quality medical insurance increases patients' chances of receiving proper medical attention and their compliance to medical treatment (Kilbourne, 2005; Carlson et al., 2006). Dr. Striph reported that some physicians found parents were against children's blood lead testing due to the lack of insurance coverage for screening (Striph, 1995). In this study, we found that children without any insurance coverage in the rural Nebraska area had higher odds of having elevated BLLs, compared to those who had private insurance coverage. This finding highlighted an environmental justice issue that children with lower socioeconomic status may be exposed to a higher level of lead exposure and thus with elevated BLLs. Additionally, the variability in coverage between private insurance, Medicaid, and self-pay may lead to parental resistance to blood lead screening. The BLLs in children without any health insurance may be underestimated.

One of the advantages of EHR data is that it identified the reasons why hospital- and clinic- admitted children had their blood lead level tested. More than 60% of the blood lead tests in this study were due to routine health screening. A higher number of preventive screenings can help the community identify and tackle lead poisoning issues earlier. We expected to find a large group of children who received blood lead tests in the Omaha area because of potential exposure to lead resources. However, there were only 52 tests done because of suspected lead exposure issues. One possible explanation of this finding could be that the environmental lead exposure has significant decreased in the Omaha area as suggested in Chapter 3. But findings in our previous studies on environmental lead resources suggested that lead can still be found in residential areas. Therefore, another reason for a low number of tests conducted due to suspected lead exposure was that most residents in Omaha might not be aware of potential lead exposure in the environment.

This study has certain limitations that should be considered. First, the final analytic samples were convenient samples collected from a hospital EHR system. The subjects were not randomly selected from the Nebraska and Omaha population. Therefore, the generalizability of this study was limited. Second, the data did not include any socioeconomic status of the subjects or any environmental sources of lead exposure measurements. These individual characteristics and environmental exposure information could have further our understanding of the risk factors of elevated BLL in Omaha. Finally, we may not have captured children in certain high-risk race/ethnicity groups, such as Hispanic and refugee children.

Conclusion

This study showed that BLL in Omaha children has decreased compared to 30 years ago. We found percentages of elevated BLL among Nebraska children higher than national data and reports. Although clinical data is more likely to present a higher prevalence of diseases than surveillance and national survey data, findings from this study are still pronounced enough to state that childhood elevated BLL is still a public health burden in Omaha, Nebraska. Additionally, children in rural Nebraska may have a higher risk of lead poisoning than children living in urban areas. Future studies should consider combining environmental lead exposure information with children's BLL data. Collaboration between research facilities, medical systems, and local health departments should be enhanced, and therefore a safe living environment can be provided to children.

CHAPTER 6: CONCLUSIONS

The U.S. has enacted multiple federal laws and regulations on controlling lead sources and preventing lead poisoning since the 1970s. From reducing and eliminating environmental lead sources perspective, the U.S. EPA regulated a phase-out of lead in gasoline in 1973 (U.S. EPA, 1973), the CPSC banned lead-based paint in residential properties in 1978 (CPSP, 1977), and the Comprehensive Environmental Response, Contamination and Liability Act (CERCLA), known as the Superfund program, was applied by the U.S. Congress in 1980 (U.S. Congress, 1980). The U.S. CDC is responsible for defining the criteria for interpreting blood lead levels (BLLs) in children. The regulatory BLL's value was changed from 40 µg/dL in the 1970s to the current standard of 5 µg/dL. As a result, environmental lead exposures and childhood blood lead levels have substantially declined in the U.S. However, many locations in the U.S. still have persistent environmental lead hazards, and children who live in these locations are more likely to be exposed to high levels of lead.

Historical lead contamination resulted in the EPA declaring 8,840 acres of Omaha, Nebraska a Superfund site in 1998. Between 1999 and 2015, the EPA completed soil cleanup activities at 13,090 residential properties where soil lead levels exceeded 400 ppm. However, contradictory findings suggested the cleanup activities might not be effective in controlling lead exposure. Additionally, the EPA's standard of soil lead clearance at 400 ppm was not adequately protective for residents. There is a need for updated knowledge of the current lead levels in environmental media in Omaha, Nebraska.

Children's exposure to lead has been a major concern in Omaha, Nebraska. The prevalence of reported elevated BLLs in Omaha children has decreased dramatically in the past 30 years. Nevertheless, most Omaha children under six years old have not received early childhood blood lead screenings. In addition, the incidence of elevated BLLs in children aged six years old and older has been underexplored. Extensive childhood BLLs data is essential for the Omaha community to understand current childhood lead poisoning status.

The three objectives of this dissertation were as follows: (1) to characterize environmental lead exposures in the soil and air of public parks; (2) to quantify lead concentrations in residential dust; and (3) evaluate BLL in children through electronic health records. The findings and conclusions of these three distinct studies are presented in the following section.

Study findings

Low levels of lead in soil and air in public parks

The first study, titled "Assessment of soil and air lead concentrations in Omaha public parks," quantified the lead concentrations in soil and air samples collected in Omaha public parks. It also presented the differences in soil and air lead concentrations between parks inside and outside the Omaha Lead Superfund site. We collected and analyzed for lead 80 composite soil samples from 62 Omaha public parks. None of these composite samples presented a soil lead concentration higher than the EPA standard of 400 ppm. Only four samples had a lead concentration that exceeded the AAP recommended standard of 50 ppm. All air lead samples showed a concentration of lead below the detection limit. There were 24 parks inside of the Omaha Lead Superfund site having historical soil lead measurement records. We found that only one of these 24 parks had current soil lead concentration higher than the historical value. The geometric mean of soil lead concentrations in these 24 parks have significantly decreased by 90.5% ($p\text{-value}<0.001$).

Average and median soil lead concentrations of public parks inside the Omaha Lead Superfund site were significantly higher than the parks outside. We did not find any atmospheric parameters associated with soil and air lead concentrations. In general, there was no significant association between the soil lead concentrations and the distance of parks to the nearest highways. However, specifically for parks inside the Superfund site, there was an inverse correlation between distance to highway and soil lead concentration, indicating we cannot reject the possibility legacy-leaded gasoline from highway traffic still impacts soil.

Elevated indoor lead dust concentrations were found in residents' homes.

The second study, "Distribution and determinants of elevated residential indoor lead dust concentration in Omaha, NE," was an investigation of lead in residential indoor dust. Among 350 eligible homes, 34.8% had a windowsill lead dust concentration equal to or higher than the EPA standard, and 35.2% of them had an elevated floor lead dust concentration. There were more homes inside of Omaha Lead Superfund site that had an elevated windowsill or floor lead dust compared to homes outside. Mean and median lead dust concentrations of homes inside of Omaha Lead Superfund site were significantly higher than those of homes outside.

We found several home and occupant characteristics were associated with elevated indoor lead dust concentration. Houses built in 1950 or earlier had the highest odds of having elevated indoor lead dust concentrations. Houses located inside the Omaha Lead Superfund site and a high level of soil lead were also exposed to higher indoor lead dust concentrations. African- American families and families without insurance coverage for adults had higher odds of elevated indoor lead dust exposures. Overall, findings from this study highlighted lead dust is still a prevalent hazard in

Omaha, Nebraska. Residents living in the Omaha Lead Superfund site and with low socioeconomic status are more likely exposed to higher levels of indoor lead dust.

Higher prevalence of children's elevated blood levels compared to national data.

In the third study, "Blood lead levels of children admitted to hospitals and clinics in Omaha, NE," we used the electronic health record data from the Nebraska Medicine system to measure children's blood lead levels. More than 3.1% of Omaha children who were admitted to hospitals or clinics and had at least one blood lead test between 2014 and 2019 had an elevated blood lead test result reported. This prevalence was higher than the national prevalence of 2.0% reported by the CDC's blood lead surveillance program. Clinical EHR data often present a higher prevalence of diseases, compared to the surveillance and national survey data. Still, findings from our third study suggested childhood elevated BLL may still be a public health burden in Omaha, NE. A higher percentage of blood lead tests reported elevated BLLs for children living in other areas of Nebraska, indicating there is a need for future studies on lead exposures in children in rural Nebraska.

Associations between gender and insurance status with children with elevated BLLs were determined in this study. We used the clinical data from the Nebraska Medicine system to determine potential determinants of elevated BLLs among Nebraska children who were admitted to a hospital or clinic and had their blood lead concentration measured. In the Greater Omaha area, girls were less common to have an elevated BLLs than boys. In the rural Nebraska area, children without insurance coverage had higher odds of having elevated BLLs. A greater percentage of children had their blood lead tested for a health screening purpose rather than disease treatment purposes. Less than 2% of children were admitted to hospitals or clinics because they had suspected exposure to lead sources.

Significance of study findings

Evidence from three studies presented environmental lead exposures in children at Omaha, Nebraska. We updated the current Omaha lead knowledge base by providing new information on the distribution and determinants of lead in soil, dust, and air. This information can be used by multiple parties, including city planners and government leaders. More importantly, the residents in Omaha need transparent information on lead exposures. We hope our findings can help residents better understand lead exposures in the community and thus help them better prevent lead poisoning. We also believe local and state health departments can use our findings on indoor lead dust concentrations to establish hazard cleanup programs to help families with potential elevated indoor lead exposure. Findings on children's BLLs pointed out existing problems and challenges in childhood lead poisoning. Continuous efforts in preventing children from lead exposure in Omaha, Nebraska are needed. Overall, this dissertation helped to address a knowledge gap by quantifying impacts of a Superfund program on environmental lead exposure. Experience from our studies and existing challenges identified during the dissertation highlighted the needs of continuous monitoring of environmental lead exposure and children’s blood lead levels, as well as developing collaboration between health departments, hospital systems, non-profit organizations, and academic researchers. Our research approaches and future study recommendations can be adapted and used in other U.S. locations with historical or current lead contaminations. We hope this dissertation will help to challenge lead-related environmental justice issues across the U.S. and improve children’s health by identifying, reducing, and eliminating lead exposure.

Strengths and limitations

There are certain strengths of our studies in this dissertation. First and foremost, all the studies were designed to evaluate the Omaha environmental lead exposures with the consideration of the lead-related children's health consequences. Together these studies demonstrated the current status of lead exposures in Omaha, Nebraska, and provided a methodology that can be used as a basis for future lead exposures research. Only a limited number of lead studies have been conducted in Omaha, Nebraska, after EPA-led actions in Omaha Lead Superfund site stopped in 2015. As a result of the EPA cleanup activities, the environment in Omaha may have changed dramatically. Therefore, new studies with new methodologies are important in demonstrating the current status of children's lead exposure and predicting health impacts on children in the future.

Our studies included collaboration with non-profit organizations and hospital systems. We believe comprehensive and transparent knowledge of lead exposures is critical not just for researchers and policymakers but also essential to residents. Lead-related data distributed in different facilities and organizations made lead-related information transparency a challenge to the community. Through our studies, we tried to sort out available and useful lead-related data and finally presented them all together in a way that residents in Omaha can better understand. The general design for this dissertation may become a foundation of future lead studies where multi-organization collaborations are required.

Previous studies in the U.S. lead Superfund sites usually concentrated on the environmental lead contamination and childhood lead poisoning status inside of Superfund sites (Sheldrake and Stifelman, 2003; von Lindern, Spalinger, Bero et al., 2003; von Lindern, Spalinger, Petroysan et al., 2003), rather than focusing the environmental impacts and health consequences on proximity to a lead Superfund site. Additionally, only a handful of studies were able to examine the effectiveness of lead cleanup activities (Sheldrake and Stifelman, 2003; von Lindern, Spalinger, Bero et al., 2003; Lanphear et al., 2003; Klemick et al., 2020). We used a complex sampling strategy to capture information for both inside and outside of the Omaha Lead Superfund site. Along with advanced statistical analysis and adjustment, we were able to present post EPA-lead Superfund program environmental lead concentrations and childhood blood lead levels in and out of the Omaha Lead Superfund site.

There are also weaknesses in our studies. There are a couple of limitations which should be highlighted. First, we were not able to link environmental lead exposures and blood lead information at the individual level. This was mainly due to the disadvantages of combining data without identifiable personal information from different sources. This weakness limited us from predicting current environmental lead exposures' impacts on children's BLLs. Another major weakness was associated with our environmental samples collection strategy. The soil samples we collected, and the dust samples collected by OHKA, were composite samples. There were several issues with the composite sampling strategy: 1) the sample may not be representative for the sampling site; 2) we were not able to determine the variability of lead concentrations at each sampling site, and 3) there was a possibility we might miss the lead-contaminated area and thus underestimate the lead exposure. The final limitation was the limited coverage of children's BLLs data. According to NE DHHS and Douglas County Health Departments, both have been actively conducting blood lead testing for children in Omaha, Nebraska. Unfortunately, we failed to acquire any children's BLL data from NE DHHS or Douglas County Health Departments. Therefore, we were not able to present more representative results at the population level on children's BLL status.

Understanding the findings and identifying the existing limitations of our study will bring valuable experience for future studies. We believe future lead studies with enhanced collaboration among multiple facilities and organizations can further our understanding of lead exposures in children, and thus we can serve our community better.

Directions of future studies

There are three potential research plans that can be carried out in the future for lead studies in Omaha, Nebraska.

Continuous lead exposure assessments and management in public facilities

Other than lead in soil and air, we can also assess lead concentrations in dust and water in public facilities. During our soil collection activities in Omaha public parks, we noticed some equipment in the playground had deteriorating paint. It is likely lead-based paint was used on older playground equipment and constructions. Researchers can collaborate with the City of Omaha to continuously monitor lead concentrations in parks' soil and dust, as well as examine the conditions of paint on playground equipment.

We recommend in Chapter 3 hand hygiene stations should be installed near the playground and populated areas in parks. A study can examine the association between children keeping hand hygiene practice by using hand hygiene stations in the parks and the lead levels on their hands and in their blood. This proposed study may bring valuable information on cost-effect prevention methods of childhood elevated BLLs.

Citizen scientists' projects to monitor residential lead exposure

An effective way to consistently monitor hazardous material at residents' homes is the citizen scientists project. In this project, researchers will provide appropriate training to the citizens, which allows citizens to accurately measure lead concentrations in certain environmental media. For example, citizen scientists can collect dust, water, and consumer product samples at their homes on a specific schedule. The samples will then be analyzed by accredited researchers, and the lead concentration results of these samples will be shared with the citizen scientists. We believe data collected by citizen scientists can provide new perspectives and possibilities for lead exposure research. This proposed research plan is also valuable to the citizen scientists themselves as these research activities can increase community awareness regarding environmental lead problems. This research project may also provide an outreach opportunity for the communities in the rural area. We identified in Chapter 5 there was a potential issue of lead poisoning in children living in rural Nebraska. We hope the research approach of citizen scientists can not only benefit researchers for better understanding environmental hazards issues in the rural area but also help the underserved population to receive useful information.

Blood lead surveillance program

Health surveillance programs are critical to the prosperity and health of a community – using data to improve health outcomes and reduce unnecessary illness and injury. The effectiveness of public health surveillance programs effectiveness depends upon characterizing quality information, generating data about the health burden in the population of questions, and timeliness.

Childhood blood lead surveillance programs provide data on children exposed to lead. These programs advise actions that families, healthcare workers, communities, and local governments can take to prevent undue illness and injury among children exposed to lead using blood lead testing and monitoring. In Nebraska, the primary surveillance statistics on children’s BLL are collected by the Nebraska Health and

Human Services Department (NE DHHS) and Douglas County Health Department (DCHD). Aggregated at best, the BLL data collected by NE DHHS and DCHD have only presented a snapshot of BLL among Nebraska children to the public, indicating the surveillance is limited in time and space. The absence of information and surveillance data does not equate to the absence of disease and injury. Characterizing the disease burden of lead exposure and toxicity among children in the community remains critical as there is no safe level of lead a child can be exposed to.

Future operations of the childhood blood lead surveillance program can consider addressing the following issues: 1) identify the challenges preventing children from receiving early and routine blood lead tests and use these findings to guide future childhood blood lead test monitoring programs; 2) increase the number of blood lead tests in the rural area and among children aged six years or older; 3) conduct environmental lead exposure assessments for children who receive a blood lead test, and identify the relationship between the environmental lead exposure information with children's BLL results; and 4) measure adults' blood lead levels and lead exposure to determine potential maternal and child's lead poisoning outcomes. All these operations demand a great number of resources, including labor, funding, and time, which may be beyond the individual organization and facility's capacity. Therefore, collaborations through equitable partnerships between local and state health departments, academic researchers, and community members need to be developed. Together, we can better serve our community and children in preventing lead poisoning and achieving the Health People 2030 objectives of reducing exposure to lead in the population.

APPENDIX A: SOIL SAMPLING PROCEDURES

Pre-sampling procedure

We donned a new pair of clean, disposable, non-powdered gloves before collecting each park's sample. We selected plastic zip-type resealable bags as the final soil sample containers. For each sampling bag, we wrote the park ID and sampling date and time on the label with a permanent ink marker.

Sampling procedure

For soil sampling, we drove the sampling metal probe into the soil surface to a depth of approximately 6 inches. We then twisted and removed the probe from the soil retaining the soil in the probe. Once, we removed the probe from the soil, we pushed out all the soil into the sampling bucket. We repeated this sampling process twice at each sampling location. During the soil sampling, we did not avoid clear and obvious paint chips, but we avoided including any grass, twigs, stones, and other debris. After all individual samples were collected, we mixed them in the sampling bucket, and then transferred the final composite soil sample into the pre-labeled zip-type resealable bag and tightly sealed the bag.

Post sampling procedure

We wiped off any excess soil from the probe using a gloved finger and cleaned the sampling probe and bucket with wet wipes and Liquinox. We then discarded the wipes and gloves in the trash bag for proper disposal away from the sampling site. Before leaving the sampling site, we made sure the zip-type resealable bag was correctly labeled with a park ID and sampling date and time. Additionally, we checked that the sampling park information on the bag appeared correctly on the site sampling field notes.

APPENDIX B: DATA MANAGEMENT FOR DIGITAL SURVEY SPREADSHEET DATA AND LEAD IN DUST REPORT DATA

Digital survey data-home's and occupant's characteristics

There were 419 homes and 239 variables in the original Omaha Healthy Kids Alliance (OHKA)'s digital survey spreadsheet. We selected our variables of interest if they were available in the spreadsheet and without more than 50% of missing values. The reasons behind the variable of interest selections were based on either of the following criteria: 1) the selected characteristic was identified as a determinant of elevated lead concentration in at least one published study (Jacobs, 1995; Frank, et al., 2019); or 2) the selected characteristic has a considerably plausible association with lead exposure.

The home's characteristics include each home's address, zip code, year of built, whether it is inside of Omaha Superfund site (yes or no), whether its soil was tested for lead (yes or no), and what the soil lead concentration was.

The following process was used to verify each variable's value, replace any missing value, and create new variables. We first verified each home's address and zip code by using the USPS Coding Accuracy Support System; any missing zip code was retrieved and replaced during this process. We then used Douglas County, Nebraska Property Record System to verify or determine when the home was originally built. Finally, we used the Omaha Lead Registry (OLR) database (Omaha Lead Registry, 2021) to verify whether the home is located inside of Omaha Superfund site and determine whether the home's soil was tested for lead and the actual soil lead concentration. We created two new variables based on the home soil lead concentration. The first soil lead variable was named *Soil Lead Concentration by Superfund Site*, which was categorized into four groups: Non-Superfund site, Superfund site-soil lead was not tested, Superfund site-soil lead concentration was lower than the U.S. EPA standard of 400 ppm for lead in bare soil in play areas (U.S. EPA, 2020a), and Superfund site-soil lead concentration was equal to or higher than 400 ppm. The second soil lead variable was named *Soil Lead Concentration by Regulatory Standards*, which was categorized into three groups: soil lead concentration lower than any regulatory standards (0 ppm ≤soil lead concentration ≤80 ppm), soil lead concentration higher than the California Department of Toxic Substances Control (DTSC)'s standard of 80 ppm (California DTSC, 2018) but lower than the EPA soil lead standard (80 ppm<soil lead concentration<400 ppm), and soil lead concentration was equal to or higher than the EPA standard (soil lead concentration≥400 ppm). If any of the original information provided by OHKA and information from public database was discrepant, we replaced the original values with the up-to-date public database information. Additionally, if the original value was missing, we also added the available public database values to the data.

The selected occupant characteristics included race/ethnicity (categorized as White Caucasian, Hispanic, American African, Asian, American Indian, Native Hawaiian/other Pacific Islander, multiple races, and prefer not to answer), household ownership (categorized as rental and owner-occupied), annual household income, whether all adults or children in the household had a primary care physician, whether adults or children had insurance and what type of insurance it was, family size, numbers of occupants under different age categories (included age less than 7, between 7 to 18, between 19 to 61, and older than 61), and current smoker at home.

The following process was used to verify and recode each variable's value and replace any missing value. Race/ethnicity was recoded into four groups: White Caucasian, Hispanic, American African, and other (which included Asian, American

Indian, Native Hawaiian/other Pacific Islander, and multiple races), because of limited observations in some minority groups. A new variable named poverty level (extreme, moderate, relative, or non-poverty) was calculated by using the participated home's annual household income, numbers of children and adult occupants, and 2017 U.S. Bureau's Poverty Thresholds (U.S. Census Bureau, 2021). Missing values were found among insurance status variables, while there was no missing in the variables of insurance type. Therefore, based on the response of insurance type, we determined substitution value for missing values in the insurance status variables.

Lead in dust report data

According to OHKA, both windowsill and floor lead dust sampling conducted at each participated home followed the EPA 2013 lead dust sampling technician guide (U.S. EPA, 2013). Samples were then analyzed by EMLS Analytical, Inc. (Cinnaminson, NJ), an Environmental Lead Laboratory Accreditation Program accredited laboratory.

We manually recorded all participated homes' lead dust concentrations into a spreadsheet. After data input, we created a new dichotomous variable to categorize whether a home had an elevated lead dust concentration. This variable was determined by examining if this home had at least one windowsill or floor dust concentration equal to or higher than the EPA dust-lead hazard standards. The U.S. EPA standards for windowsills and floor lead dust concentrations are 100 $\mu g/ft^2$ and10 $\mu g/ft^2$, respectively (U.S. EPA, 2020a).

APPENDIX C: THE RESULTS OF MARGINAL AND RANDOM-EFFECTS MODELS FOR NEBRASKA CHILDREN WHO RECEIVED A BLOOD LEAD TEST DURING THEIR VISITS TO HOSPITALS OR CLINICS, 2014-2019.

	Greater Omaha Area				Rest of Nebraska			
	Marginal model		Random-effects model		Marginal model		Random-effects model	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	-2.712**	0.221	-2.939**	0.218	-2.346**	0.178	-2.637**	0.155
Age group								
Less than 6 (Ref.)								
Aged 6 and older	0.793	0.606	0.093	0.439	0.618	0.584	0.705	0.587
Gender								
Male (Ref.)								
Female	-0.263	0.266	-0.296	0.227	0.445**	0.218	-0.334	0.209
Insurance								
Private								
Medicaid	0.270	0.276	0.273	0.281	0.359	0.268	0.292	0.239
Self-pay	0.129	0.362	0.194	0.332	1.221**	0.341	0.715	0.403
Race[a]								
White Caucasian (Ref.)								
African American	0.001	0.286	-0.103	0.246	0.001	0.748	-0.095	0.772
Other	-0.376	0.372	-0.292	0.380	-0.651	0.474	-0.502	0.484
Unknown	0.263	0.698	0.352	0.609	-0.045	0.524	-0.061	0.477

Notes: Both marginal and random-effects models were conducted by using the generalize estimating equation approach. SE=standard error; **p-value<0.05.

[a] Other race/ethnicity included Asian, Hispanic, American Indian, Alaska Native, Native Hawaiian/Pacific Islander, multiracial, and other. Unknown included patient refused to answer and unknown.

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