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Environmental Injustice? Disparities in the Exposure to Environmental Lead Poisoning and Risks among Children in the Chicago Neighborhoods

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Abstract Lead (Pb), the useful metal element of the natural environment, can be poisonous when it is absorbed by the body. In the United States, lead poisoning remains a major concern to children, especially in Chicago where still 1 out of every 6 children is affected. Therefore, the goal of this study is to evaluate the spatial distribution of aggregated children's elevated BLLs in Chicago's neighborhoods and its relationship with the social-economic, behavioral, and cognitive risk factors. Geovisualization, geospatial pattern analysis, and spatially-resolved spatial modeling tools built-in ArcGIS were used. Accordingly, significant geographical control of the BLLs was detected such that lower BLLs were detected in the central, northern, far northern, and southwestern sides of the city, while the higher BLLs were detected in the western, southern, and southwestern sides of the city (i.e., I = 0.34, permutation 999, and p-value 0.001). This distribution has shown statistically significant associations (i.e., R^2 = 40 – 54; and $P < 0.05$), with the social-economic, behavioral, and cognitive variables, indicating the likelihood of incidences of violent crimes, poverty, minority, and lower students' performances, in the higher BLLs areas. However, it is not clear if these factors' associations imply causations to the higher/lower BLLs or vice versa. Therefore, further studies would be critical to establishing, how many of these associations are the causations.

Keywords: *lead poisoning, Blood Lead Level (BLL), environmental injustice, African American Children, Chicago*

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1. Introduction

According to [1], environmental injustice is the disproportionate exposition of minorities and low-income communities to a point and non-point source of environmental pollution. It is the phenomenon of the uneven protection of environmental hazards and unequal decision-making capabilities for living, learning, and working in a healthy environment. In Chicago, historical discrimination in housing, redlining, and land-use decision-making capabilities have made minorities and low-income Chicagoans fall victim to the industrialization of residential areas and the adverse consequences of environmental hazards thereof [2]. Such disproportionate exposure is evident in relatively higher incidences of chronic health conditions such as but not limited to cancer, asthma, and lead poisoning.

Lead (Pb) is a naturally occurring metal element in our environment. Because of its properties (i.e., soft, malleable, ductile, poorly electroconductive, bluish-white, and lustrous) lead has various use for humanity [3,4]. For example, Lead is used for making pipes and ammunitions, ingredients of paints, a constituent of batteries, and a monitor of computer and television screens [3]. It is also applied as a coloring element in ceramic glasses, electrodes in the process of electrolysis, and weight in sports equipment [3]. Despite all these uses, lead is poisonous, when it enters the body and accumulates to a dangerous amount in the blood [5]. Lead enters the body mainly through foods, drinking water, and breathing air [3,5]. According to [6], spatially dependent environmental risk factors for lead poisoning are observed in a home built before 1978. Close to 87% of Chicago homes were built before 1978, the year lead-based paint was outlawed [7,8].

Lead exposure has serious impacts on human health [3,9,10,11]. It disrupts the biosynthesis of hemoglobin and anemia and causes a rise in blood pressure, kidney damage, miscarriages, subtle abortions, and disruption of nervous systems [10,11]. It can also cause brain damage, and declining fertility in men through sperm damage [3]. Neuropsychological and biological studies find that sufficient exposure to lead is associated with the alteration of neurotransmitter and hormonal systems in ways that may induce aggressive and violent behavior [9]. Other impacts of the exposure include impaired cardiovascular, immunological, and endocrine [12], renal, and hepatic systems [13]. Damage to the body, from exposure to lead poisoning, is irreversible, but treatment could prevent further aggravation.

The quantity of blood lead levels (BLLs) regarded as environmentally poisoning lead has evolved over the past 60 years [5,9,14,15]. In 1960, the threshold was set at 60 micrograms of lead per deciliter of blood (mg/dL), however, soon "silent lead poisoning" in children with BLLs was below the designated threshold [9]. As more and more reports were documented on the deficits threshold, the Center for Disease Control and Prevention (CDC) lowered the tolerable BLLs. In 1970, a new threshold i.e., 40 mg/dL was established, and by 1991, it was further reduced to 10 mg/dL [5,14]. As of 2012, the CDC lowered the threshold from 10 to 5mg/dL; and recently there are no tolerable BLLs [15].

Lead poisoning can wreak havoc in young children more so than in adults [3,11,16,17,18,19,20]. It can start when it enters the fetus through the mother's placenta and cause various damage to the nervous system of the unborn child [3]. Lead inhibits the bodies of growing children from absorbing iron, zinc, and calcium, minerals essential to proper brain and nerve development [16]. In general, children being more susceptible to lead exposure is reflected in its negative influence on brain development and the nervous system. Long-term exposure in young children could result in cognitive challenges, and behavioral disruptions, such as aggression, impulsive behavior, and hyperactivity [17,19,20,21]. Additionally, another health effect of concern in children is Attention Deficit Hyperactivity Disorder (ADHD), which is characterized by delayed or diminished learning ability, and lower IQ, which impacts students' school performance [20,22]. According to the data from the National Toxicology Program (NTP), the concurrent effect of the BLLs on IQ may even be direr than it is currently believed. Several studies have reported the human impact of exposure to elevated lead levels and poisoning thereof [10,23,24]. It accounts for 0.6% of the global burden of disease [10,23], and an estimated 4 million children, within the United States, live in homes (i.e., environments) that are exposed to lead [24]. According to Hauptman [25], 500,000 children, below 6 years of age, have BLLs greater than or equal to 5 µg/dL, in the United States and over 80,000 of these children are found in Chicago.

Several studies also show that hazards from lead exposure are prevalent in poor and minority-dominated neighborhoods [6,9,26,27,28]. Needleman [9] showed lead-induced adverse Health outcomes as conditioned by the communities' income inequality. According to Needleman [9], poverty and disparities are major concerns surrounding the long-term effects of the environmental hazards of lead poisoning. Similarly, Reed [28], found a greater likelihood of lead exposure in troubled neighborhoods with poor diets and low psychological well-being. According to Reed [28] even though evidence suggests that minorities and the poor are not disproportionately exposed to lead, still they are more affected by its ill-effects than whites and their affluent counterparts [28]. The poor and minorities have fewer access to physicians, and treatments that are inadequate or incomplete. Besides, the affluent population often does a better job at lead risk assessments, screening, and mandated follow-ups [28]. The economic burden of environmental hazards of lead poisoning is enormous (e.g., [25]). The economic cost of the cognitive impairment associated with elevated BLLs is $50.9 billion annually and the medical treatment and educational services for a lead-exposed child are in the order of $5600 [25]. Therefore, the main goal of this research is to assess the spatially resolved association of geographically varying distribution of elevated BLLs, among Chicago's 77 neighborhoods, and the social-economic, behavioral, and cognitive risk factors. Geographic Information Systems (GIS), has proven to be extremely beneficial in studying the geographical distribution of such phenomena. Additionally, spatial regression modeling is an established statistical method used to examine relationships between two spatial variables: explanatory vs. response variables.

2. Materials and Methods

2.1. Description of Study Area

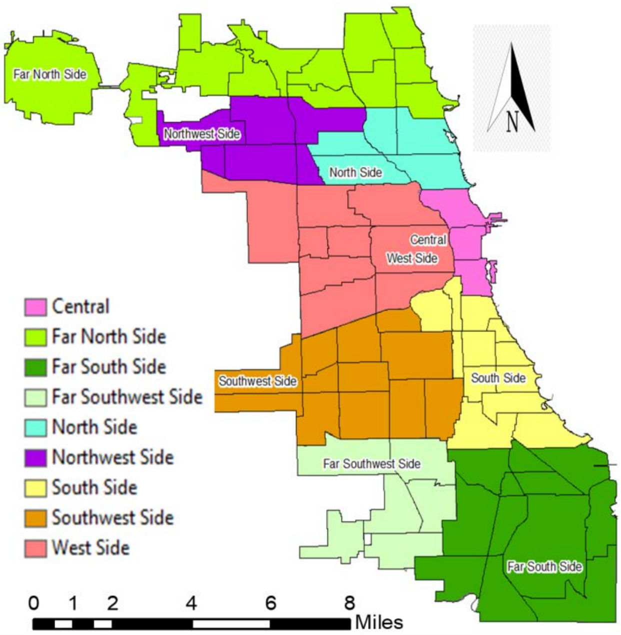

Figure 1. Study Area

The city of Chicago covers just over two hundred and thirty-one square miles, approximately five hundred and seventy feet above sea level. It is situated along the shore of Lake Michigan, the 5th largest body of fresh water in the world. The city was incorporated as a city in 1837 and currently has a population that amounts to over two million people, the third-largest city in the United States. The city is also divided into 9 districts namely: Central, north, far north, northwest, west, southwest, far southwest, south, and far south sides. These districts are generally classified along Chicago's racially segregated fault lines. It is also partitioned into 77 different neighborhoods. The Chicago neighborhoods were partitioned by the University of Chicago's social science research committee for the city's statistical and planning purposes. Accordingly, the neighborhoods are a geographical scale at which various socio-economic, demographic and environmental statistical data are traditionally aggregated and widely used by the city to assist the local and regional urban planning.

2.2. Data Description and Acquisition

This study deployed the data on blood lead levels among children aged 0 – 6 in Chicago, students' performances on statewide test scores, and crime occurrence rates. Additionally, it used the percent African American population, the population below the poverty level, per capita income, and values of the Hardship index. These data are aggregated at the scale of Chicago neighborhoods for geo-analysis. Although the data analyses were conducted at the scale of the neighborhoods, the results were interpreted at the scale of Chicago districts.

2.2.1. Blood lead Levels (BLLs), Poverty Rate, and Per Capital Income

The blood lead levels (BLLs), population below poverty level, and per capita incomes were obtained from Chicago Health Atlas (https://www.chicagohealthatlas.org/). The city of Chicago and the Chicago department of health together prepared and maintains the Chicago health atlas data for better understanding, monitoring, and solutions for improved Chicago health and well-being. The aggregated BLLs value of children aged 0 – 6 is measured in micrograms of lead per deciliter of blood (mg/dL) and is listed under the category of the environmental health of the atlas. On the other hand, the per capita income, and poverty rates, are listed under the income category of the socio-economic factors. The data were aggregated at the scale of neighborhood community areas of Chicago. The Per capita income is the average income earned by individuals, whereas the poverty rate is the ratio of the number of people whose income falls below the poverty line. The poverty line is a threshold nationally defined as when a household income of family size of four earns less than $26,200 per annum.

2.2.2. Illinois Standards Achievement Test (ISAT)

The data for the Illinois Standards Achievement Test (ISAT) for the city of Chicago was obtained from Chicago public schools (https://www.cps.edu/about/district-data/metrics/assessment-reports/). The ISAT data is used for assessing the learning standards of Illinois students and aggregated by schools in the city. It is consisted of the students' assessment of Math, reading, and writing tests and is reported as the percent of students exceeding the standards needed. The scores are expressed in the percentile ranks, which range from as low as 1 to the maximum of 99%, with 50% denoting a school's average performance. The school aggregated performance ranks for math, reading, and writing tests were averaged to get estimates of the overall ISAT scores of schools in the city. The school performances were averaged across the community areas in preparation for further analysis.

2.2.3. Violent crime Incidences

Data for crime incidence reports are created by the research & development division of the Chicago Police and were obtained from the city of Chicago data portal (https://data.cityofchicago.org/). The crime data is prepared by the Chicago police department's Citizen Law Enforcement Analysis and Reporting (CLEAR) system. A spreadsheet containing incidences of 265,268 crimes was downloaded, of which 56,725 were violent crimes, i.e., offenses committed against a person. According to the state of Illinois, violent crimes include incidences of battery, robbery, burglary, arson, child abuse, endangerment, homicide, kidnapping, rape, assaults, and offenses. Violent crime data has a coordinate point for the location where the crimes were committed. The add XY event data tool of ArcGIS is used to geocode the point data, which was joined with the base map of neighborhoods layer with spatial join. The spatial join returned a spatially-resolved summary of the number of violent crime incidences for each neighborhood of the city.

2.2.4. Percent African American Population

The percent African American population data were obtained from the US census bureau data portal (https://www.census.gov/programs-surveys/acs/data.html). The data is collected by American Community Survey (ACS), which gathers demographic data used for monitoring and conducting public services planning. The data is available at many geographic aggregate levels depending on the survey frequency. This study used a 5-years ACS survey, which presents demographic (i.e., ancestry, citizenship, educational attainment, income, language proficiency, migration, disability, employment, and housing characteristic) data on a scale of the census tract. Parallel census tract boundary data of Chicago, to which the tabular demographic data is joined, was obtained from Topologically Integrated Geographic Encoding and Referencing (TIGER) Line Shapefiles data (https://www.census.gov/geographies/mapping-files.html). The two data joined and aggregated into the scale of the Chicago neighborhood area. Percent African American population is a quotient of African American population to the total population of each neighborhood as follows:

$$P_a = \frac{Pop_a}{P_t} \quad (1)$$

Where P_a is the percent African American population of the neighborhoods, Pop_a total African American population in the neighborhoods, and P_t total population of the neighborhood

2.2.5. Hardship Index

The hardship index is a measure that is used for comparing socio-economic conditions by combining six social and economic variables [29,30]. These are unemployment rate (i.e., percent of the unemployed population over 16 years of age); educational achievement (i.e., ratio of population ages 25 or above without a high school diploma); and per capita income (i.e., individual income per annum). It also includes dependency ratio (the proportion of population below age 18 and above 64);

crowded housing (i.e., percentage of the housing units, where more than a person lives in a room), and poverty (i.e., the proportion of the population below designated state's poverty level). The hardship index is calculated by standardizing the socio-economic variables (e.g., unemployment rate) using the following equation

$$X = \left(\left(Y - Ymin \right) / \left(Ymax - Ymin \right) \right) * 100 \quad (2)$$

Where, X = the standardized unemployment rate of the neighborhood community areas of Chicago; Y = the unemployment rate of the neighborhood community areas; Ymin = the value of the minimum unemployment rate of all neighborhood community areas of Chicago; and Ymax = the value of the maximum unemployment rate of all neighborhood community areas of Chicago.

The final hardship index is the average of the standard values ranging between 0 and 100. Zero means neighborhoods experiencing the least socioeconomic hardship, while 100 means neighborhoods experiencing stressful socioeconomic hardship.

2.3. Research Methodology

3.3.1. Spatial Analysis of Aggregated Blood Lead Levels (BLLs) among the Children Aged 0 – 6 years of Chicago Neighborhoods

The spatial analysis of the aggregated BLLs values of the children in the Chicago neighborhood was conducted via visual interpretation and geostatistical analysis. Other studies have used similar techniques to interpret and analyze the geographical phenomenon in space [31,32,33]. The visual interpretation of aggregated BLLs (i.e., deciliter of blood (mg/dL)) was made after the data was displayed as a choropleth map in GIS. The data is classified into five categories with class boundaries defined around the city's, state's, and national averages.

On the other hand, the geostatistical analysis was conducted using the pattern analysis tools of global as well as local Moran's I statistics, both found built in a spatial statistics toolbox in ArcGIS. The Global Moran's I is a statistical tool used for measuring the tendency that proximate urban neighborhoods are having similar, dissimilar, and random values of the BLLs. The statistics of Global Moran's I index [34,35] is estimated by.

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}\left[X_i - \bar{X}\right]\left[X_j - \bar{X}\right]}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i.j}\right)\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2} \quad (3)$$

Where: I is the Moran's I statistics, X_i is the values of the aggregated BLL values among the children of Chicago neighborhoods i and X_j the values of the BLLs among the children of urban neighborhoods j and, $W_{i,j}$ is the spatial weight that determines the relationship between urban neighborhoods i and j , n is equal to the total number of urban neighborhoods. The statistical significance of the spatial pattern is established by comparing the observed Moran's I statistics with the expected Moran's I of the random distribution. The Expected Moran's I ($E(I)$) is given by:

$$E(I) = \frac{-1}{n-1} \quad (4)$$

The local Moran's I statistics, conversely, is a measure of the local hot or cold spots of the aggregated BLLs values. The hotspots are areas where clusters of higher aggregated BLL values are detected, while the coldspots are localities, where clusters of lower values. The statistical tool deployed to measure the local Moran's I_i statistics is Anselin Local Moran's (I_i) [34,35,36], and is expressed as:

$$I_i = \frac{X_i - \bar{X}}{S_i^2}\sum_{j=1}^{n} W_{i,j}\left(x_i - \bar{X}\right) \quad (5)$$

Where: X_i is the values of the BLLs among the children of Chicago neighborhoods i, $\bar{X}$is the mean of the aggregated BLLs values; and $W_{i,j}$, is the spatial weight between neighborhoods i and j and S_i^2 is a standard deviation value of the neighborhoods BLLs given by.

$$S_i^2 = \frac{\sum_{j=1}^{n}\left(X_j - \bar{X}\right)^2}{n-1} \quad (6)$$

The standard deviation is a measure of the standardized variation of the aggregated BLL values of neighborhoods from their mean value.

3.3.2. Modelling Spatial Associations of the Aggregated BLL among Children (i.e., 1 – 6 Ages) and Associated Social-economic, Behavioral, Cognitive Risk Factors

The spatial associations of the aggregated BLLs and risk factors were conducted globally using simple spatial regression models, and locally by the Geographical Weighted Regression (GWR) models (Kunene, 2016; Kunene, et al., 2018). The simple spatial regression is an extension of a regular Ordinary Least Square (OLS) regression, with an extension of spatial weight structure. The spatial weight defined the structure to account for the non-stationarity in the data, i., e., a situation where aggregated BLLs' mean and variance are dependent on the location and distance between neighborhoods. Finally, the global model predicted neighborhoods' aggregated BLL among children of Chicago as influenced by values of social-economic, behavioral, and cognitive risk factors.

On the other hand, GWR establishes a local association between the aggregated BLL values and risk factor(s). The GWR works based on a simple premise to model local goodness-of-fit from subsets of the neighborhoods' BLLs and the risk factors. The number of neighborhoods considered for the estimation is contingent on the size of the moving window (i.e., Kernel type, Bandwidth method, Distance, and Number of neighbors' parameters). This model also accounts for a nonstationary, while also estimating the unbiased slope, and intercept for the association. The equation to estimate the dependent aggregated BLLs among children Vj from a set of n social-economic, behavioral, and cognitive factors Zi, for a neighborhood pi is locally given by [37] as follows:

$$\hat{V}_j = a_j + \beta_j z_j + \epsilon_j \quad (7)$$

$$a_j = \frac{\sum_{i=i}^{n} w_{ij} z_i^2 \sum_{i=1}^{n} w_{ij} v_i - \sum_{i=1}^{n} w_{ij} \sum_{i=1}^{n} w_{ij} z_i v_i}{\sum_{i=1}^{n} w_{ij} \sum_{i=1}^{n} w_{ij} z_i^2 - \left(\sum_{i=1}^{n} w_{ij} z_i\right)^2} \quad (8)$$

$$\beta_j = \frac{\sum_{i=i}^{n} w_{ij} \sum_{i=1}^{n} w_{ij} z_i v_i - \sum_{i=1}^{n} w_{ij} z_i \sum_{i=1}^{n} w_{ij} v_i}{\sum_{i=1}^{n} w_{ij} \sum_{i=1}^{n} w_{ij} z_i^2 - \left(\sum_{i=1}^{n} w_{ij} z_i\right)^2} \quad (9)$$

Where: a_j is the intercept, βj is the beta coefficient and ε_j is the error term of the regression equation. The observed values Vi are weighted by W_{ij} indicating the spatial weights for the input data of the target neighborhood P_i.

Simply spatial weights are often estimated by giving a weight of 1 for the neighborhoods that fall within the spatial kernel and 0 for that outside. However, in this study adaptive kernel i.e., Gaussian weighting scheme, where the weight assigned to neighbor decrease with distances is applied. The adaptive kernel (Gaussian) is given by:

$$W_{i,j} = e^{\frac{1}{2}\left(\frac{d_{i,j}}{b}\right)^2} \quad (10)$$

Where: W_{ij} are weights of the neighborhood areas in Chicago with respect to the target neighborhood P_i and $d_{i,j}$ are neighborhoods distances from the target and b is “bandwidth.

3.3.3. Validation Methods

The spatial autocorrelation and hot spot analysis (i.e., Getis-Ord Gi* statistics) of the aggregated BLLs values were verified by the values of the Moran’s I Index and corresponding p-value. Generally, while positive 1 Moran's Index value indicates spatial clustering of the aggregated BLLs value; the index values near negative1.0 indicate spatial dispersion, and 0 indexes depict spatial randomness. P-values (i.e., $\alpha < 0.05$) ascertain the statistical significance of the observed patterns of dispersion or cluster in the distribution of the aggregated BLL values. On the other hand, various indices were deployed to evaluate the performances of the spatial regressions. Generally, the indices validated the associations in terms of strengths, directions, and their statistical significance. The relative strengths of the associations were evaluated with the coefficient of determination (R^2), while the directions were validated by the positivity or negativity of the β-coefficient. The statistical significances of the associations were denoted by P-values (i.e., $\alpha < 0.05$).

3. Results and Discussion

3.1. Blood Lead Levels (BLLs) among the Children aged 0 – 6 Years in the Chicago Neighborhoods

Figure 2 shows the spatial distribution of the aggregated BLLs among Children aged 0 – 6 in Chicago neighborhoods. Accordingly, the BLLs values range between 0 – 7.90 micrograms of lead per deciliter of blood (mg/dL). The citywide average BLLs among children is μ = 1.9 mg/dL ± σ = 1.85. Twelve neighborhoods (i.e., 16%) have the lowest BLLs values (i.e., 0 mg/dL) and 48 neighborhoods (i.e., 62%) have the BLLs values below average. Fuller Park neighborhood on the south side exhibited the highest aggregated BLLs value (i.e., 7.90 mg/dL) and 29 neighborhoods have the BLLs above average. This is higher than the average national (i.e., 1.6 mg/dL) as well as the Illinois State’s (i.e., (i.e., 1.3 mg/dL) BLLs among children aged 0 – 6. Generally, the spatial patterns of the BLLs among children are distributed in such a way that lower levels are found in the central, northern, far northern, and southwestern districts of the city while the higher values are found in the western, southern, and southwestern districts; where racial minorities and low-income Chicagoans dominate.

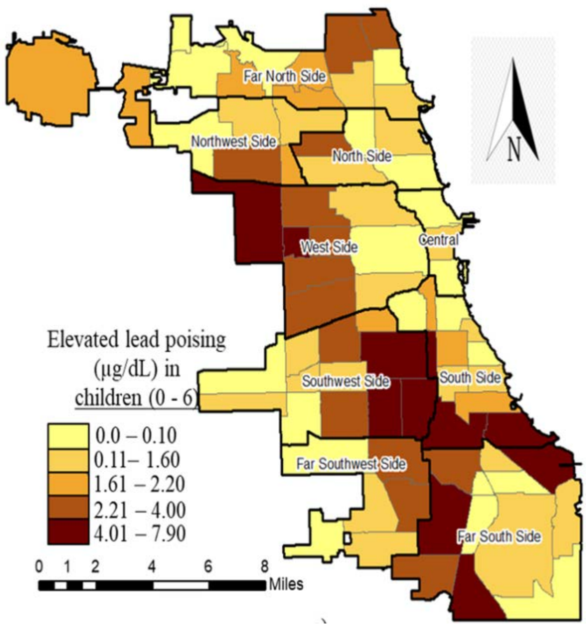

Figure 2. A map showing the spatial pattern and distribution of the BLLs among Children below age 6 and below in the 77 Chicago neighborhoods

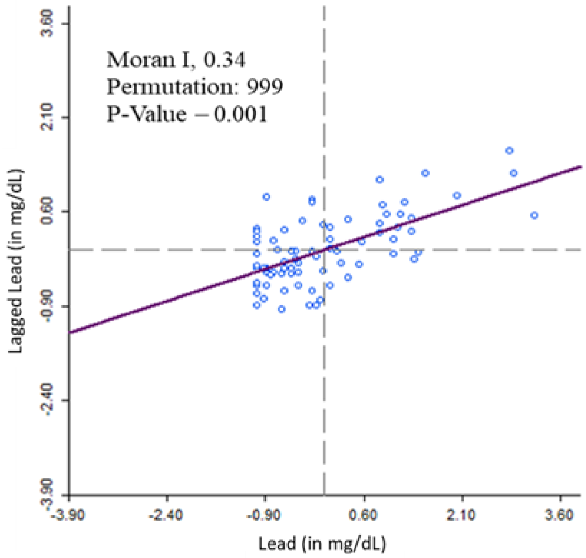

Figure 3. Graph showing spatial autocorrelation (Moran’s I) of the spatial patterns of the BLLs among children 6 years and below in Chicago neighborhoods

Therefore, further analysis was conducted to see if there were statistically significant geographical biases in the patterns of the aggregated BLL values distribution (i.e., see Figure 3). Accordingly, the global spatial autocorrelation (i.e., Moran's I statistics) analysis was conducted and found significant positive Moran's I (i.e., I = 0.34, permutation 999, and p-value 0.001). The outcome is indicative of the aggregated BLLs values' non- dispersed and non-randomness. On the other hand, the positive Moran's I coefficient suggests the spatial clustering of the similar values (i.e., high or low) of the aggregated BLLs values

Additionally, the Local Moran's statistic is conducted to analyze spatially-resolved locations of neighborhoods where significant spatial clustering is present (i.e., Figure 4). Accordingly, significant clustering of the higher values of the aggregated BLLs (i.e., in the south, far southwest, southwest, and far south sides of Chicago), as well as the low values, were observed (i.e., p-value = 0.05; See Figure 5). These districts are known for their predominant residence of the minority (i.e., Blacks and Hispanic Americans) and low-income population. Conversely, the neighborhoods in the central, north, and far north districts, where the White population predominantly resides, showed significant clustering of the low values of the aggregated BLLs (Figure 5). This clearly demonstrates the element of injustice in the city regarding the disproportionate exposure of minorities and low-income Chicagoans to the impact of environmental lead poisoning.

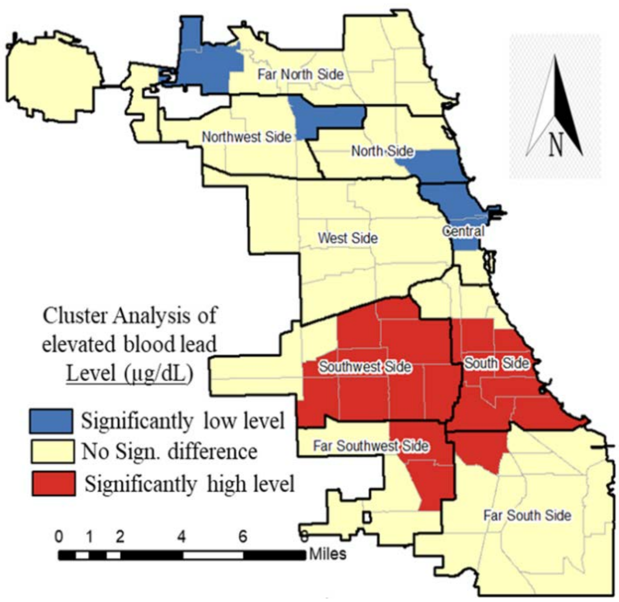

Figure 4. Map showing the spatial clustering of similar values of the BLLs among Children 6 years and below in Chicago neighborhoods

The geographical controls of the BLLs among children and the disproportionate exposition of minorities are consistent with studies conducted in Texas [38] Greater Flint, Michigan [39] Baltimore Maryland [40] and in Kabwe, Zambia [41]. It is also consistent with reported demographic control of the environmental exposure of children in the state of Illinois [41]. According to [41], although the average children's (i.e., age 0 – 6) BLLs are lower for the state of Illinois, the BLLs among African American and Hispanic children are reported to be 3 and 2 times the level among racially White children.

Table 1. Relationships of blood lead level among the children and ISAT score and Crime Occurrence Rate

Variables	Strength (R^2)	The direction of the relationship (B- coefficient)	Local Variability (Sigma)	Significance of the relationship (P-value)
Average ISAT Score	0.40	-0.08	1.607	0.000
Crime Occurrence Rate	0.53	0.007	1.103	0.000

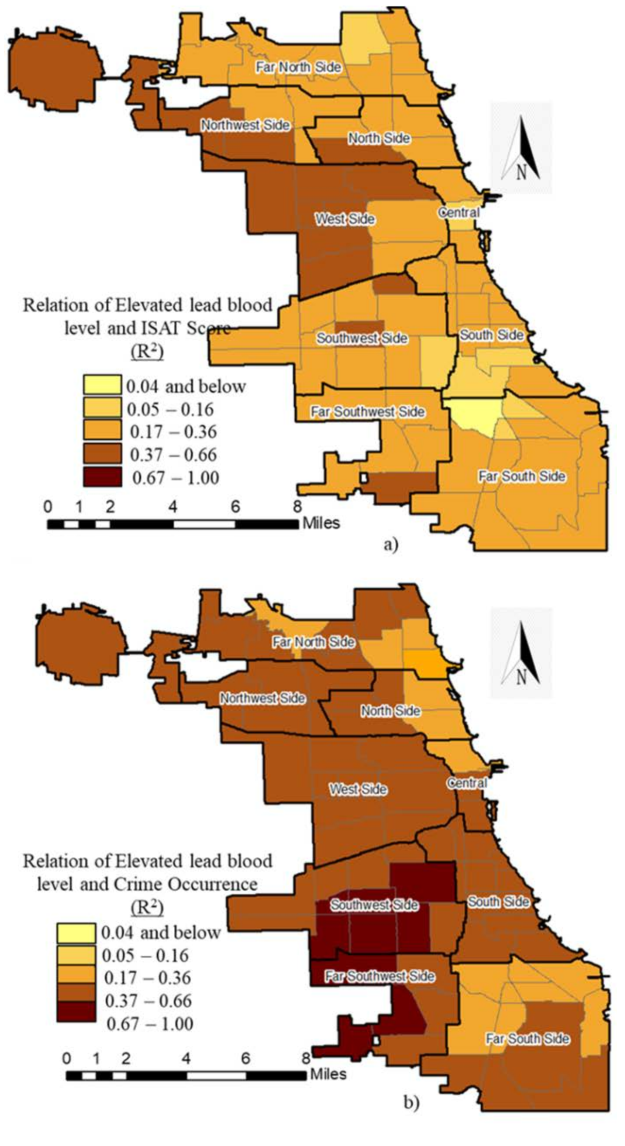

Figure 5. Geographically Weighted Spatial Relationships of elevated BLLs and the crime occurrence and students' test scores for the 77 community areas of Chicago.

However, such relations are locally variable across the city (Figure 5). The local association (i.e., R^2) of the aggregated neighborhood's BLLs values among children and crime occurrence rate (per 1000 residents) ranged between R^2 of 20% and 88% (i.e., moderate to very strong associations). Moderate associations (R^2 = 16% - 36%) were observed in the neighborhoods of the north, far northern, and far southern sides of the city; whereas a very strong association (R^2 > 67%) was established in the southwest and far southwest sides. Similarly, the local association (i.e., R^2) of the BLLs among children and averaged ISAT scores ranged between R^2 of 5% and 47% (i.e., weak to moderate associations). The weak association was observed in the neighborhood of Chatham, on the far south side of Chicago, while the moderate associations (i.e., R^2 = 16% - 36%) dominated the west and northwest sides, indicating the relative strong associations in the neighborhoods with lower BLLs values. The relationship corroborates the association observed between childhood leads exposure and academic achievement: evidence in Detroit public schools [43] and behaviors of gun violence, homicide, and rape observed in St. Louis City, MO [44].

3.2. Analyzing the Spatial Relationships between Elevated Lead Blood Levels and Socioeconomic Characteristics of the Chicago Neighborhoods

Table 2 determined the association of demographic and socio-economic factors with aggregated BLL values. Accordingly, variables such as percent African American population, population below the poverty line, household income, and hardship index were found statistically significant associations (i.e., $P < 0.05$), although the direction and the strength of the associations vary from variable to variable. The highest associations were found with the percent population below the poverty line (i.e., R^2 = 54%), followed by hardship index (i.e., R^2 = 47%; strong relation) and household per capita income (i.e., R^2 = 42%)., while the association with the percent African population was the least (i.e., R^2 = 40%). On the other hand, the association with the percent African American, percent population below poverty lines, and hardship index were positive; where it was negative with the household income.

Table 2. Spatial Relationships of percent older African American population and percent African American and total population in Chicagoland

Variables	Strength (R^2)	The direction of the relationship (B- coefficient)	Local Variability (Sigma)	Significance of the relationship (P-value)
Percent African American	0.40	0.02	1.6	0.000
Below poverty	0.54	0.11	1.4	0.000
Per Capital Income	0.42	-0.0006	1.5	0.000
Hardship Index	0.50	0.04	1.4	0.000

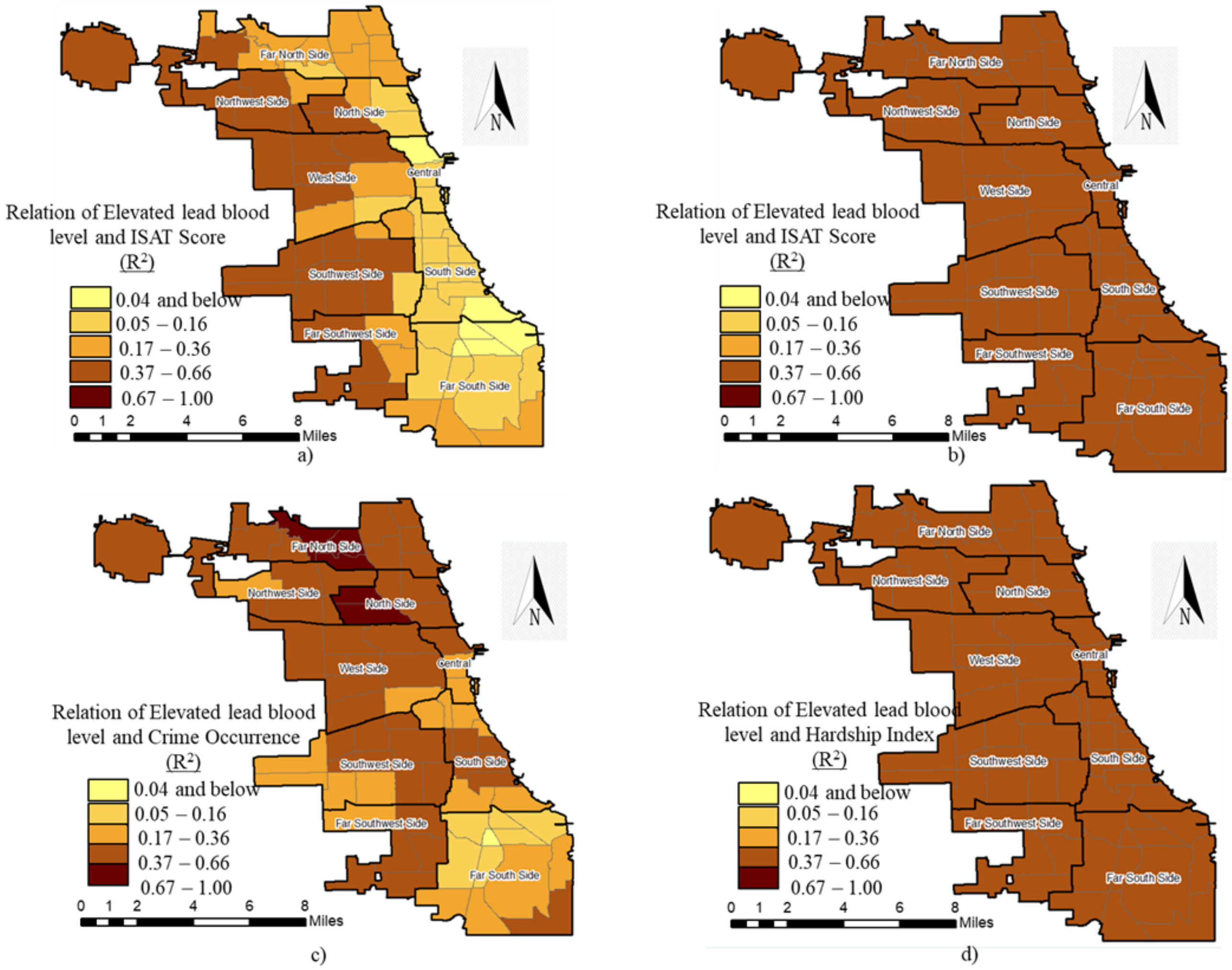

Figure 6. Geographically Weighted Spatial Relationships of elevated BLLs: a) percent African American population, b) economic hardship index, c) population's percent below the poverty line, and d) household per Capital income of the community areas of Chicago

However, the spatially-resolved local strengths of the associations with neighborhood aggregated BLL values are dynamic over space (Figure 6). For example, the local association (i.e., R^2) with household income ranged between R^2 of 4% and 73% (i.e., very weak to very strong associations). The very strong associations (R^2 = 37% - 66%) were detected in the north and far north sides neighborhoods, while very weak and weak associations (R^2 = 2% - 16%) are detected in the far south sides. Additionally, the local association (i.e., R^2) with a percent African American population ranged between R^2 of 2% and 65% (i.e., very weak to strong associations). The strong associations (R^2 = 37% - 66%) were detected in the neighborhoods of the northwestern, west, southwest and far southwestern; while very weak and weak associations (R^2 = 2% - 16%) are detected in the central, south, and far south districts, indicating the model is a good predictor for neighborhoods with low aggregated BLLs. The observed local associations corroborate the findings reported elsewhere [6,27,45]. For instance, [45] reported the associations of demographic and socioeconomic factors with the BLLs values of Mexican-American children and adolescents in the United States. Similarly, [27] also documented BLLs associated with the oldest house age and poorest housing condition in Flint, MI; while [6] showed the association of a low socioeconomic status with the higher BLLs values among Korean Children, although the underlying mechanism was not known.

4. Conclusion

This study evaluated the spatial distribution of children's aggregated BLL values in Chicago's neighborhoods. The spatial patterns of the aggregated BLL values are distributed in such a way that lower levels are found in the neighborhoods of the central, northern, far northern, and southwestern districts of the city, while the higher values are found in the neighborhoods of the western, southern, and southwestern districts. Further analysis was conducted to see if the spatial variations were geographically controlled (i.e., Moran's I statistics) and established a significant positive control (i.e., I = 0.34, permutation 999, and p-value 0.001. Additionally, the spatial associations of aggregated BLL values and the social-economic, behavioral, and cognitive factors were established. Accordingly, significant associations were found between aggregated ISAT scores and the BLL (i.e., P-value < 0.05). Similarly, a significant association was also observed between neighborhoods of the BLLs and the violent crime incidence rate (per 1000 residents) (i.e., P-value < 0.05). The higher strength of association was found with the crime incidence rate (i.e., R^2 = 53%) vis-à-vis the ISAT score (i.e., R^2 = 40%). Besides, while the association with the average ISAT scores is negative, the association with the crime occurrence rate is positive. This indicates that higher aggregated BLLs values signify the likelihood of higher criminal activity occurrences and poor students' performances in learning. Moreover, the associations with percent African American population, population below the poverty line, household income, and hardship index were significant (i.e., R^2 = 40 - 54; P < 0.05). While the associations with the percent African American, percent population below poverty lines, and hardship index were positive; the association with household income, was negative indicating that the higher aggregated BLLs values imply the prospect of poorer and blacker Chicago neighborhoods.

These findings are important amid the announcement by the CDC that there are no safe levels of blood lead, a testament to the severity of lead's environmental hazard. It is particularly critical for Chicago neighborhoods considering that 87% of the homes were built before when lead-based paint is outlawed, and hence this continues to be a major health issue for Chicagoans. The observed geographical controls of the Chicago neighborhoods' BLLs distribution are critical to identifying neighborhoods where lead prevention and management operations are tailored. Additionally, the associated social-economic, behavioral, and cognitive risk factors are also important proxies to locate neighborhoods with exposure to environmental lead hazards. Although significant, the research has some limitations. For example, the strong associations of the aggregated BLL values and the evaluated risk factors cannot be directly translated into causations. Therefore, the percent African American population, population below the poverty line, household income, and hardship index may not be responsible for elevated BLLs or vice versa. Further studies will be critical to establishing, how many of these associations are the causations.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. Besides, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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