Distribution Agreement

In presenting this thesis as a partial fulfillment of the requirements for a degree from Emory University, I hereby grant to Emory University and its agents the non-exclusive license to archive, make accessible, and display my thesis in whole or in part in all forms of media, now or hereafter now, including display on the World Wide Web. I understand that I may select some access restrictions as part of the online submission of this thesis. I retain all ownership rights to the copyright of the thesis. I also retain the right to use in future works (such as articles or books) all or part of this thesis.

Samantha Distler   April 6, 2020

Assessing Low-Level Lead Exposure Risk in Atlanta, Georgia

by

Samantha Distler

Eri Saikawa
Adviser

Quantitative Sciences

Eri Saikawa

Adviser

W. Michael Caudle

Committee Member

Jeremy Jacobson

Committee Member

2020

Assessing Low-Level Lead Exposure Risk in Atlanta, Georgia

By

Samantha Distler

Eri Saikawa

Adviser

An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
Bachelor of Science with Honors

Quantitative Sciences

2020

Abstract

Assessing Low-Level Lead Exposure Risk in Atlanta, Georgia
By Samantha Distler

Lead poisoning is often seen as a problem of the past. While acute cases are now rare, there is no safe level of lead and blood lead levels at and below 5 µg/dL are associated with neurological deficits. Previous work has established that risk factors for lead exposure include race/ethnicity, poverty, Medicaid enrollment, housing built before 1950, and age. Pockets of poverty and old housing in the greater Atlanta area put some children at particularly high risk for chronic exposure to low levels of lead. Here, 20 years of data on children's blood lead levels in Georgia were used to create maps to assess the spatial distribution of blood lead screening and blood lead levels in the Atlanta area. ZIP code-level screening rates continue to be associated with relative poverty but not with housing age, a well-established risk factor for lead exposure. Building on previous research, a priority screening index based on poverty and housing age was also created to identify specific high-risk census tracts within Atlanta ZIP codes. This index shows a cluster of eight highest-priority census tracts in Atlanta's westside a low income historically disadvantaged area. This cluster of census tracts contains 1220 children under six years old, 0.8% of all children under six years old in the greater Atlanta area.

Assessing Low-Level Lead Exposure Risk in Atlanta, Georgia

By

Samantha Distler

Eri Saikawa

Adviser

A thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
Bachelor of Science with Honors

Quantitative Sciences

2020

Acknowledgements

I would like to thank my advisor, Dr. Eri Saikawa, for her guidance throughout this project and her years of invaluable mentorship. I am also grateful to Dr. W. Michael Caudle and Dr. Jeremy Jacobson for sharing their time and expertise as members of my thesis committee. I would also like to thank all the members of the Saikawa lab, past and present, for their thoughtful comments and camaraderie. Finally, I am eternally grateful to my friends and family for all their patience and encouragement.

Table of Contents

Illustrations

Figures

Tables

INTRODUCTION

Lead, one of the oldest known toxins, affects every organ system in the human body (ATSDR, 2019; Caito & Aschner, 2015). Many of the most concerning effects of lead are neurological. High (60 to 300 µg/dL) blood lead levels (BLLs) are associated with severe neurologic outcomes like peripheral neuropathy and encephalopathy with symptoms that include ataxia, convulsions, coma, and death (ATSDR, 2019; Caito & Aschner, 2015). Such severe cases are now rare in the United States due to federal regulations that reduced lead in paint, solder, gasoline, and other common exposure sources (Brody et al., 1994; Jones et al., 2009; Pirkle, 1994). However, ongoing work continues to indicate that far lower BLLs are also associated with negative health concerns. Low-level lead exposure has been associated with immunological and endocrine effects, as well as cardiovascular disease, a major cause of adult mortality in the United States (ACCLPP, 2012; Lanphear et al., 2018). Neurologically, lower BLLs are associated with attention deficit hyperactivity disorder (ADHD), impulsivity, cognitive deficits, IQ decrements, and neuromotor changes (ATSDR, 2019; Caito & Aschner, 2015).

Lead poisoning was clinically defined until the Surgeon General's 1971 report stated that a BLL of 40 µg/dL indicated "undue absorption" of lead (US Public Health Service, 1971). In the following decades, this threshold was repeatedly lowered until a 1991 Centers for Disease Control and Prevention (CDC) policy defined the BLL of concern as 10 µg/dL (CDC, 1991). In 2012 the CDC moved away from a "level of concern" in favor of a "reference value" based on the 97.5[th] percentile BLL in children between 1-5 years (ACCLPP, 2012). This blood lead reference value was calculated as 5 µg/dL based on National Health and Nutrition Examination Survey (NHANES) data from 2007-2010 (CDC, 2013). One major reason for switching from a

static threshold level to a relative reference value was to reflect the now widely-accepted idea that there is no safe level of lead.

While there is no safe level of exposure for anyone, lead poses especially high risk for children. Young children are most likely to ingest lead due to their physical proximity to surface dust and behaviors like crawling and hand-to-mouth activity (ATSDR, 2019; EPA, 2013). Once ingested, children also absorb up to five to ten times more lead in the gastrointestinal tract than adults (Alexander et al., 1974; James et al., 1985; Ziegler et al., 1978). Absorbed lead then enters children and infants' developing nervous systems which is particularly vulnerable in part because the blood-brain barrier is not fully formed (ATSDR, 1999; Review: McCabe, 1979). Lead is known to disrupt processes like neuronal migration and synapse pruning that are crucial for brain development (ATSDR, 2019; Caito & Aschner, 2015; World Health Organization, 2010).

Decades of research have shown that some children have an even higher risk of lead exposure than others. Living in older housing is a risk factor for lead exposure because of the possible presence of lead-based paints. Residential paints containing more than 0.06% lead were banned in 1978 (CPSC, 1996). While all homes built before 1978 have an increased risk for lead exposure, houses built before 1950 pose the greatest danger as they are more likely to contain lead-based paint and that paint is more likely to contain higher levels of lead (CDC, 1997b). Certain demographic groups are also at an increased risk for lead exposure due to lack of resources and a long history of American environmental injustice. Socioeconomic factors associated with an increased risk for lead exposure include poverty, race/ethnicity (specifically, being non-Hispanic black), and Medicaid coverage (Jones et al., 2009; Sargent et al., 1995). Bernard & McGeehin (2003) found that these well-documented socioeconomic risk factors and

housing age continue to be associated with elevated BLLs even when the newer, lower BLL of 5 μg/dL is used as a reference value.

When they proposed using a reference value the CDC's Advisory Committee on Childhood Lead Poisoning Prevention (ACCLPP) stressed the importance of primary prevention and reducing disparities based on housing, race/ethnicity, and socioeconomic factors (ACCLPP, 2012). The CDC has recommended targeting high risk children and neighborhoods since 1997 (CDC, 1997b). Now, given the overall decline in BLLs in the larger US population, effectively targeting high-risk communities is more important than ever to reach those at risk for subtler chronic exposures.

Several papers have assessed methods for targeting high risk children and locations. Some researchers have focused on building regression models to predict BLLs based on demographic characteristics, like race, age, Medicaid coverage, and income (Jones et al., 2009; Kaplowitz et al., 2010; Sargent et al., 1995). Other targeting methods stress the use of geographic information systems (GIS) to create maps highlighting areas with high proportions of older homes and/or elevated BLLs (Reissman et al., 2001; Roberts et al., 2003). Different studies have assessed lead exposure at the level of counties, ZIP codes, census tracts, communities, block groups, tax parcels, and neighborhoods (Haley & Talbot, 2004; Kemper et al., 2005; Reissman et al., 2001; Roberts et al., 2003; Sargent et al., 1995, 1997). Smaller geographic areas may be able to better explain BLLs because they capture a more specific area. Research has indicated that census tracts and census block groups better explain BLLs than zip codes (Kaplowitz et al., 2010; Krieger et al., 2003). When risk is only assessed for large areas, aggregate values can obscure pockets of high risk.

In Atlanta, Georgia, the presence of risk factors, such as older housing, poverty, and high-density urban areas put some children at risk for lead exposure. Vaidyanathan et al. (2009) developed a geospatial strategy to assess Atlanta lead screening rates and results by neighborhoods since these areas are both small and easily recognizable. Using data from 2005, the authors created a priority screening index of Atlanta neighborhoods using housing age and enrollment in Georgia's Special Supplemental Nutrition Program for Women, Infants, and Children (WIC), a proxy for poverty. To indicate the urgency of lead screening, this index assigns every geographic area a score from 2 to 8 based on housing age and WIC quantile breaks. The authors also analyzed existing screening rates and found that neighborhood blood lead testing did rise with increasing WIC enrollment but was not significantly associated with the proportion of houses built before 1950 or 1978.

The Georgia Department of Public Health (DPH) recommends that all children enrolled in Medicaid receive blood lead tests at age one and two or anytime between ages three and six if no record of previous testing exists (Georgia DPH, 2016). Furthermore, the most recent guidelines state that DPH is focused on screening children who are in a high-risk group (such as WIC enrollment) or geographic location. For high-risk geographic locations, the DPH website lists 14 counties where children "may have a higher risk of lead exposure" (Georgia DPH, 2016).

These counties are the 14 high-risk counties identified in Rustin et al. (2015). In this paper the authors used GIS to create maps of Georgia based on housing age and occupancy type (owning vs renting), two components of housing-based lead exposure risk. However, the authors do not use this housing information to label counties as high risk. Instead, the raw number of children with BLLs above 5 μg/dL in 2013 was used to identify the 14 counties. Thus, many of these counties are those with the most children under six years old and/or the most children

screened. The authors note that the map highlighting these 14 counties, an updated version of a similar map of 2010 data, is meant to be added to the housing age maps. However, so far no combined map exists (Georgia DPH, 2016).

The overwhelming drop in children's BLLs in the US is arguably one of the greatest public health achievements in the nation's history (CDC, 1997a). In order to continue to further that progress in this new era of lower-level chronic exposures, state and local authorities must be able to identify high-risk areas. Despite characteristics of the Atlanta area putting children at potentially high risk for lead exposure, there is no simple, replicable system for using available data to identify specific high-risk areas and target them for blood lead screening. Here, twenty years of data from the DPH and the U.S. Census Bureau is used to understand children's BLLs and lead screening in the greater Atlanta area and construct a priority screening index to direct targeted testing.

METHODS

All BLL data used here comes from DPH and refers to children under six years old. ZIP code-level data were requested through the DPH Public Health Information Portal while county level data was retrieved from reports published on the DPH website. At the county level, children were stratified by BLLs above or below the value of 5 μg/dL from 2013 to 2018. From 1998-2012, the county-level BLLs were striated as 10-19 μg/dL and greater than or equal to 20 μg/dL. At the ZIP code level, the data contained counts of children with BLLs below 5 μg/dL and equal to or above 5 μg/dL from 1998-2018. Due to privacy policies, any count of five or fewer children in a given geographic area is suppressed. When possible, missing values were calculated as the difference between the total children screened and the complimentary strata if that value would not be directly reported or otherwise pose a risk of identifying individuals.

All demographic data (including population counts, median household income, income to poverty ratio, and housing age) were retrieved from the U.S. Census Bureau. Demographic data for the years 2000 and 2010 came from the decennial census. Otherwise, data were retrieved from the appropriate 5-year American Community Survey (ACS). Only the decennial census includes estimates of the number of children by single-year ages, so the proportion of children screened by age was only calculated for the years 2000 and 2010. All data were accessed via the Census API and analyzed in R (R Core Team, 2019). Median household income values were adjusted for inflation to be in 2018 USD. These adjustments were made according to the formula in the 2018 ACS General Handbook with the updated Consumer Price Index Research Series Using Current Methods for All items (Bureau of Labor Statistics, 2018; US Census Bureau, 2018a).

All maps were created using R and the open source mapping library Leaflet. The geographic boundaries used for mapping ZIP code and census tract level data were retrieved as shapefiles from the US Census Bureau's TIGER/Line Shapefile web interface (US Census Bureau, n.d.). For each map, the appropriate geographic boundaries were retrieved for the year of the data plotted. All geographic comparisons and overlaps were made according to the US Department of Housing and Urban Development United States Postal Service (HUD-USPS) ZIP Code Crosswalk Files (HUD, 2019).

For analysis of ZIP code data, all ACS and census data were retrieved for 5-digit ZIP code tabulation areas (ZCTAs) which the Census Bureau defines as "generalized areal representations of United States Postal Service ZIP Code service areas" (US Census Bureau, 2018b). The ACS began in 2005, but 2011 5-year estimates were the first available at the ZCTA level. In this paper, the term ZCTAs and ZIP codes are used interchangeably. The greater Atlanta

area was defined based on the ZIP codes that loosely fall within the circle formed by highway 285 (see appendix for Table S1 and Figures S1 and S2). The census tracts that correspond to this list of ZIP codes (based on HUD-USPS Crosswalk Files) were used to define the greater Atlanta area at the census tract level.

To assess the effectiveness of targeted blood lead screening, the income to poverty level ratio (IPR) was used as a measure of relative poverty. IPRs are calculated as income before taxes in the past 12 months divided by the poverty threshold which the Census Bureau assigns (in inflation-adjusted US dollars) based on the size and age of family members. The US Census Bureau reports IPRs in discrete buckets (e.g. households with IPRs from 1.00 to 1.24). Like past research, the proportion of a population with an IPR over 1.25 was used as a proxy measure for a ZIP code's relative poverty (McClure et al., 2016). Since higher IPRs indicate more income above the poverty level, this proportion is negatively associated with relative poverty. For example, as there is more relative poverty in a given area there is a lower proportion of people with IPRs over 1.25.

Assessing housing age is also important for understanding lead exposure risk because older homes are more likely to contain lead-based paint. Here, the proportion of houses built before 1950 was used as the measure of older housing. This proportion was calculated using the ACS estimate of the number of housing units built before 1950 divided by the total housing units.

The blood lead screening rate for every ZIP code was calculated as the total number of children screened according to DPH BLL data divided by the ACS estimate of the total number of children under 6 years of age. The Kruskal-Wallis test of association was used to test the association between two key risk factors (relative poverty and housing) and ZIP code screening

rates. To assess the simultaneous effects of these factors, a linear regression was run for screening rates on the proportion of houses built before 1950 and the proportion of people with IPRs above 1.25. Additional linear regressions for screening rate that included racial indicators (e.g. the proportion of the population that is non-Hispanic black) were also evaluated.

Finally, a simple priority screening index ranging from 2-8 like the one used by Vaidyanathan et al. (2009) was created. This index was primarily applied to census tracts as they allow intra-ZIP code analysis of small, specific areas. For comparison, the indexing system was also applied to Georgia ZIP codes and counties. Each index value is the sum of the geographic area's risk score for housing age and relative poverty. The housing age risk score was assigned based on the quantile breaks in the proportion of housing built before 1950 (i.e. 0th to 25th percentile = housing risk of 1, 25th to 50th percentile = 2, 50th to 75th percentile = 3, and 75th to 100th percentile = 4). The relative poverty risk score was assigned based on quantile breaks in the proportion of the population with an IPR above 1.25. However, these poverty risk scores were reversed because lower proportions indicate more poverty and higher risk (i.e. 0th to 25th percentile = housing risk of 4, 25th to 50th percentile = 3, 50th to 75th percentile = 2, and 75th to 100th percentile = 1). Since both of these values are based on quantile breaks, a given area's risk scores (and, therefore, overall priority screening index value) is dependent on the reference universe of data used to calculate the index. This same index was also applied to census tracts across the state of Georgia and the entire United States to identify tracts that consistently have the highest priority screening index values.

RESULTS

Between 1998 and 2018, DPH reported a total of 1,657,269 blood lead tests. The total number of children screened in a given year ranged between 17,634 to 127,749. The number of

children screened per year has varied widely (mean = 78,917; standard deviation = 39,278) but has generally increased over time (see Figure S3). Halfway through this time period, there was a large jump when the total number of children screened nearly doubled from 64,914 in 2008 to 122,606 in 2009. The proportion of children with BLLs above 5 μg/dL ranged from 39% (in 1998) to 1.1% (2018).

While all of the children screened were under six years old, every year at least 49.7% of the screened children were under two years old and at least 65.2% were under three years old. Figure 1 shows the density of children under one and two years old that were screened in Atlanta ZIP codes in the last two census years. In both age groups, this density was far more right skewed in 2000 compared to 2010. Neither age group came close to complete screening in either year. The maximum percentage of children screened in a ZIP code was 53% for 0-12 month-old children (ZIP code 30315 in the year 2000) and 56% for 12-24 month old children (ZIP code 30329 in 2010). For racial analysis, BLL observations are striated by DPH into four groups: black, white, other, and unknown. The statewide proportion of children screened who were black ranged from 1.6% in 1998 to 37% in 2005. The proportion of screened children who were white ranged from 0.005% in 1998 to 47.5% in 2005.
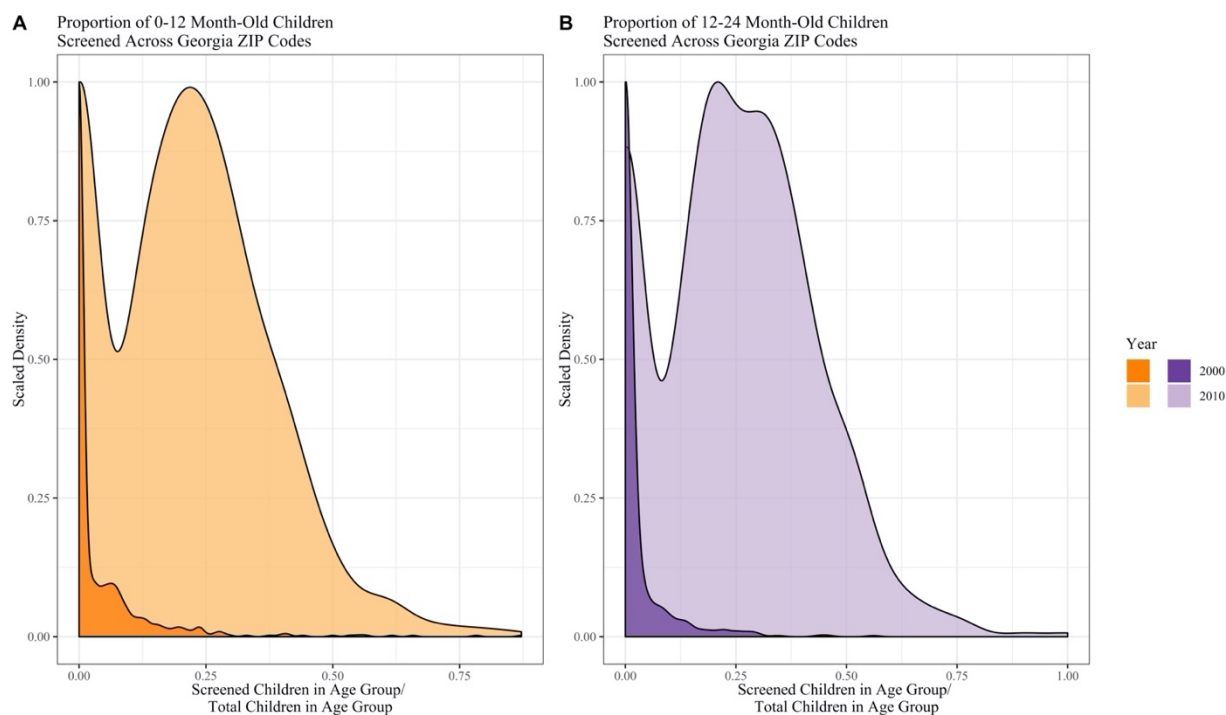
Figure 1: Distribution of the Proportion of Children Screened in 2000 and 2010 for (A) 0-12 Month-Olds and (B) 12-24 Month-Olds

Overall, 72,570 (4.4%) of screened children were missing a ZIP code and, therefore, excluded from all ZIP code-level analyses. In the period when ZIP code-level ACS data were available (2011 to 2018), the proportion of children screened in ZIP codes ranged from 0.99% to 66.7% with a median of 12.7%. The ZIP code-level proportion of screened children with BLLs above 5 µg/dL ranged from 0 to 13.3% with a median of 1.5%. To visualize these changes over time, Figure 2 shows a series of maps illustrating the proportion of children screened and the proportion with BLLs above 5 µg/dL. These values are layered on top of median household income to demonstrate the connection between lead exposure and wealth. Figure 2 shows these maps for the most recent year with data available (2018) and the two most recent census years (2000 and 2010). Overall, these maps reflect that the proportion of screened children with BLLs above 5 µg/dL has generally decreased while the proportion of children screened has stabilized.
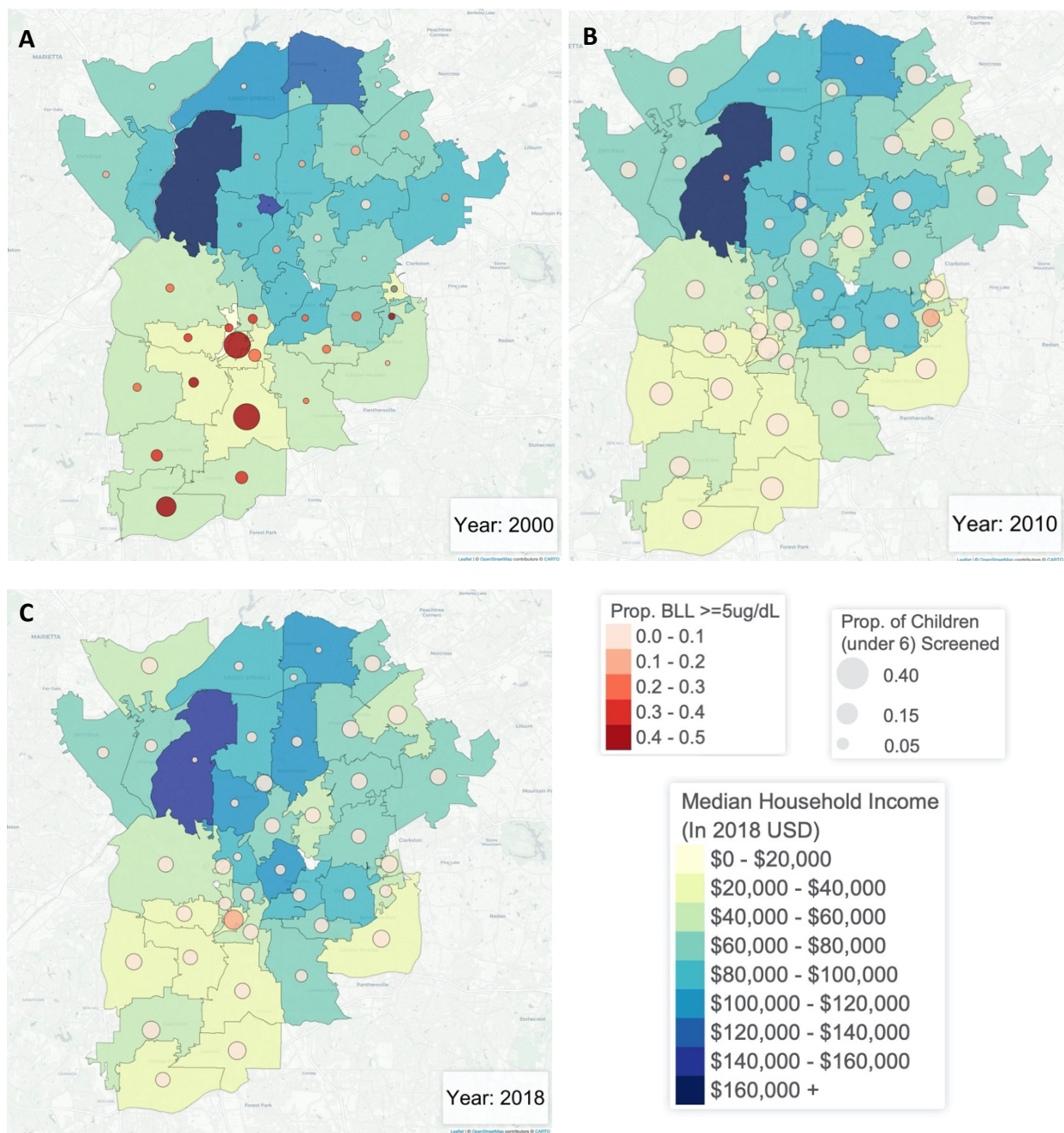
Figure 2: Layered Maps for 2000, 2010, and 2018 Proportion of Children Screened and Proportion of Screened Children with Blood Lead Levels at or above 5 μg/dL in Greater Atlanta Area ZIP codes by Median Household Income

From 2011 to 2018, the proportion of screened children with BLLs at or above 5 μg/dL in Atlanta ZIP codes was positively correlated with the proportion of housing built before 1950 (Pearson correlation = 0.17; p-value = 0.0017) and negatively associated with the proportion of

people with IPRs over 1.25 (Pearson correlation = -0.15; p-value = 0.0050). In those same years,

blood lead screening rates were not significantly associated with increasing proportions of

housing built before 1950 (Kruskal-Wallis p-value = 0.4077). However, screening rates were

significantly associated with ZIP codes' quantile score for proportion of people with IPRs over

1.25 (Kruskal-Wallis p-value = < 2.2 x 10^{-16}). A linear regression to assess the simultaneous

contributions of these risk factors indicated that housing age continues to be insignificant while

relative poverty is still statistically significantly associated with screening rates when housing

age is accounted for. These findings are consistent with the findings by Vaidyanathan et al.

(2009) that poverty (in their case, WIC enrollment) but not housing age is significantly

associated with screening rates when these factors are assessed individually or together in a

linear regression.

In addition to housing age and relative poverty, it is also important to understand if other

factors are associated with screening rates. I created two additional regression models that each

assesses screening rates by housing age, relative poverty, and a racial indicator (Table 1). While

all of the models have a modest adjusted R^2, the proportion of housing built before 1950 was not

significantly associated with the proportion screened in any model. In contrast, the proportion of

people who are not white and the proportion of people who are non-Hispanic black were both

significant in the respective models. Model 2 included the proportion of people who are not

white and had a slightly larger adjusted R^2 value than Model 1, which only included housing age

and relative poverty (0.364 and 0.358, respectively). Model 3 had the largest adjusted R^2 (0.387).

This model includes the proportion of people who are non-Hispanic black, a demographic that

has been associated with elevated BLLs (Dixon et al., 2009; Jones et al., 2009; Raymond et al.,

2014). The effect size is modest but the proportion of people who are non-Hispanic black was

significant and had a negative coefficient. This indicates that, holding the housing age and relative poverty indicators constant, the proportion of children screened is somewhat lower in ZIP codes with a higher proportion of non-Hispanic black people.

	Dependent variable:		
	Proportion of Children Screened		
	Model 1	Model 2	Model 3
Proportion Housing Built Before 1950	0.00003	−0.005	0.017
	(0.026)	(0.026)	(0.026)
Proportion IPR > 1.25	−0.345***	−0.429***	−0.483***
	(0.028)	(0.051)	(0.044)
Proportion Non-Hispanic Black			−0.087***
			(0.021)
Proportion Non-white		−0.054**	
		(0.027)	
Year	−0.006***	−0.006***	−0.006***
	(0.002)	(0.002)	(0.002)
Constant	12.876***	12.326***	12.036***
	(3.176)	(3.174)	(3.110)
Observations	327	327	327
R^2	0.364	0.371	0.395
Adjusted R^2	0.358	0.364	0.387
Residual Std. Error	0.065 (df = 323)	0.065 (df = 322)	0.064 (df = 322)
F Statistic	61.543*** (df = 3; 323)	47.573*** (df = 4; 322)	52.464*** (df = 4; 322)

Note: *p<0.1; **p<0.05; ***p<0.01

Table 1: Linear Regression Models for the Proportion of Children Screened in Greater Atlanta ZIP Codes

When applied to 2013 county level data, the priority screening index created here did not assign any of the 14 high risk counties the highest index value of 8. Only one (Troup County) of the counties identified by Rustin et al. was assigned an index value of 7 (see Figure S5). A key advantage of creating a priority screening index is that it is not just limited to counties, which are large geographic areas that may contain smaller areas with distinctly different lead exposure risk. Here, this priority screening index was applied to counties, ZIP codes, and census tracts. Figure 3 shows the priority screening index values of Fulton County, the most populous county in Georgia, and its underlying areas all using the state of Georgia as the reference universe. Panel A shows that when the index is applied at the county level, Fulton County is assigned the second-

lowest index value of 3. However, panels B, C, and D show that underneath this value the county is quite heterogeneous. The different ZIP codes across the county (panel B) and the even finer census tracts within ZIP code 30318 (panels C and D, highlighted in panel B) reveal pockets of high-risk areas that were not reflected at the county level.
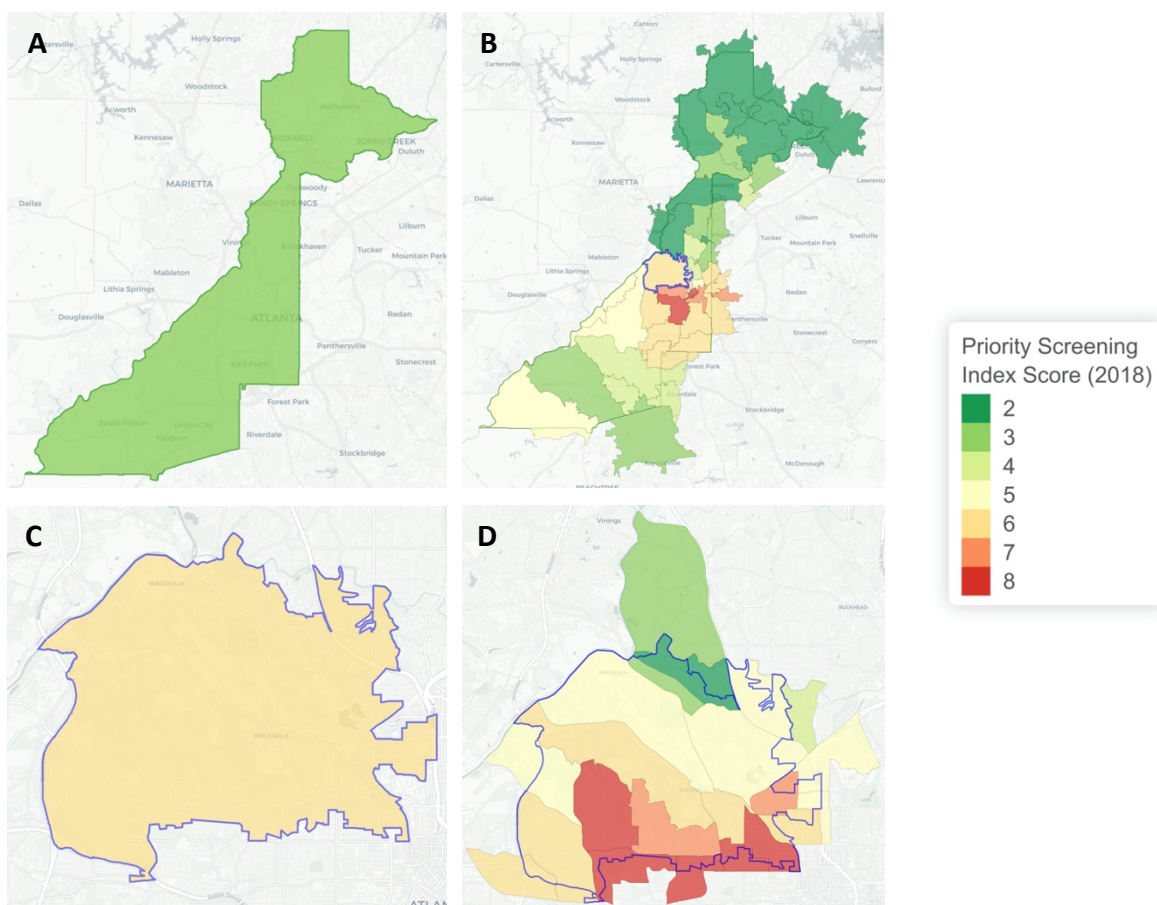

Figure 3: Hierarchical Priority Screening Index Values for (A) Fulton County, (B) ZIP Codes in Fulton County, (C) ZIP Code 30318, and (D) Census Tracts in ZIP Code 30318

Analyzing lead exposure risk at the census tract level across the greater Atlanta area reveals a cluster of high-risk census tracts in the westside of Atlanta (Figure 4). Of a total 159 tracts, nine were given the highest priority index value of 8 and 23 were assigned a value of 7. Since priority screening index values can change depending on the universe the index is applied to, recalculating the index based on different reference universes is one way to evaluate results.

Figure 4 shows the priority screening index values of Atlanta area census tracts in 2018 as calculated when the reference universe is the greater Atlanta area (panel A), Georgia (panel B), and the entire United States (panel C). While some Atlanta census tracts show increasingly lower PSI values, the westside of Atlanta continues to have the highest priority values (7 and 8), suggesting that screening this area is of the highest priority.
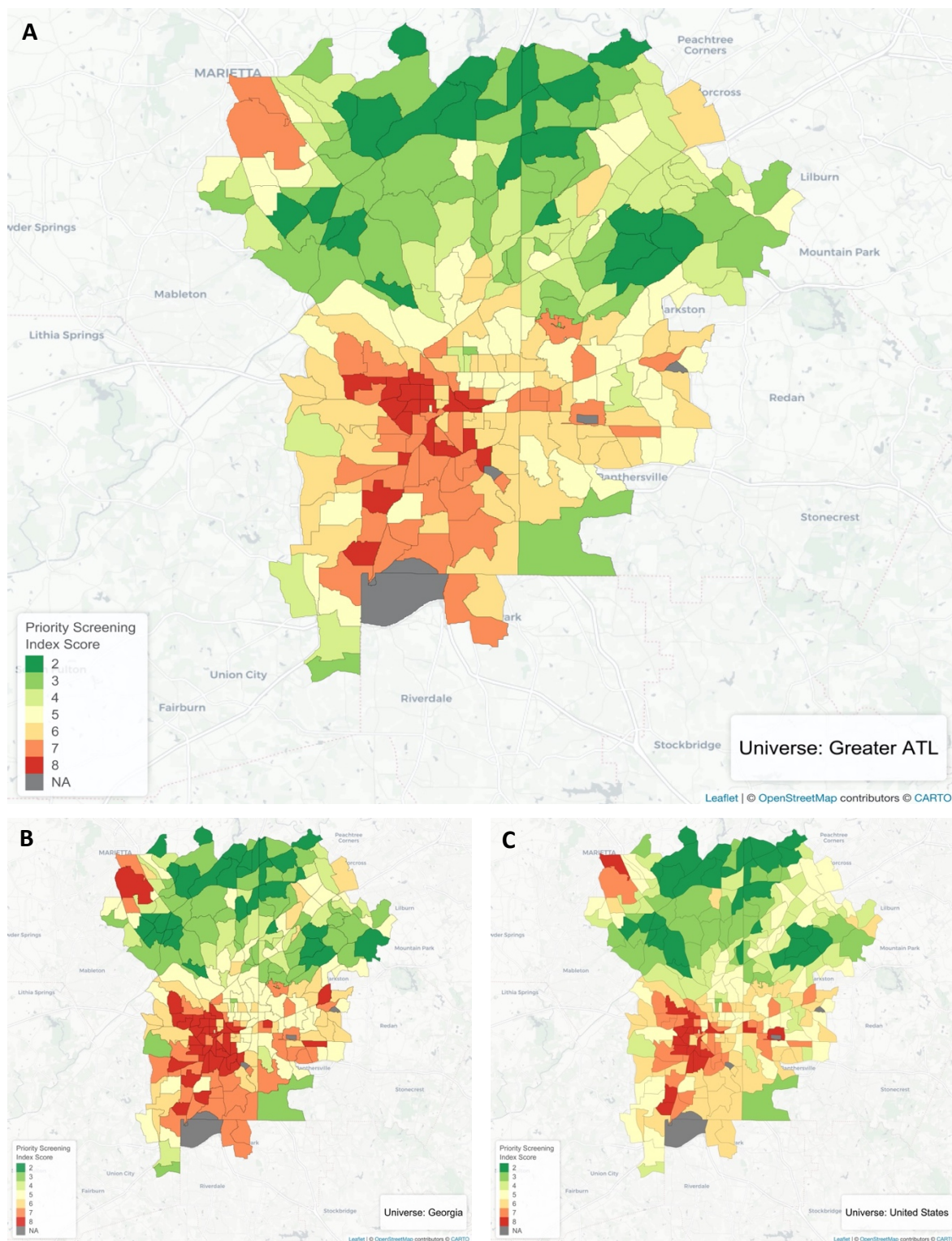
Figure 4: Priority Screening Index for Greater Atlanta Area Census Tracts in 2018 when the Reference Universe is (A) Greater Atlanta, (B) Georgia, and (C) the United States

Some areas outside of Atlanta with clusters of high-risk tracts include western Savannah, southeastern Macon, and central Athens (Figure 5), with the state as the reference universe. In addition to these urban areas, there are also high priority census tracts along the southern section of the Georgia-Alabama border.
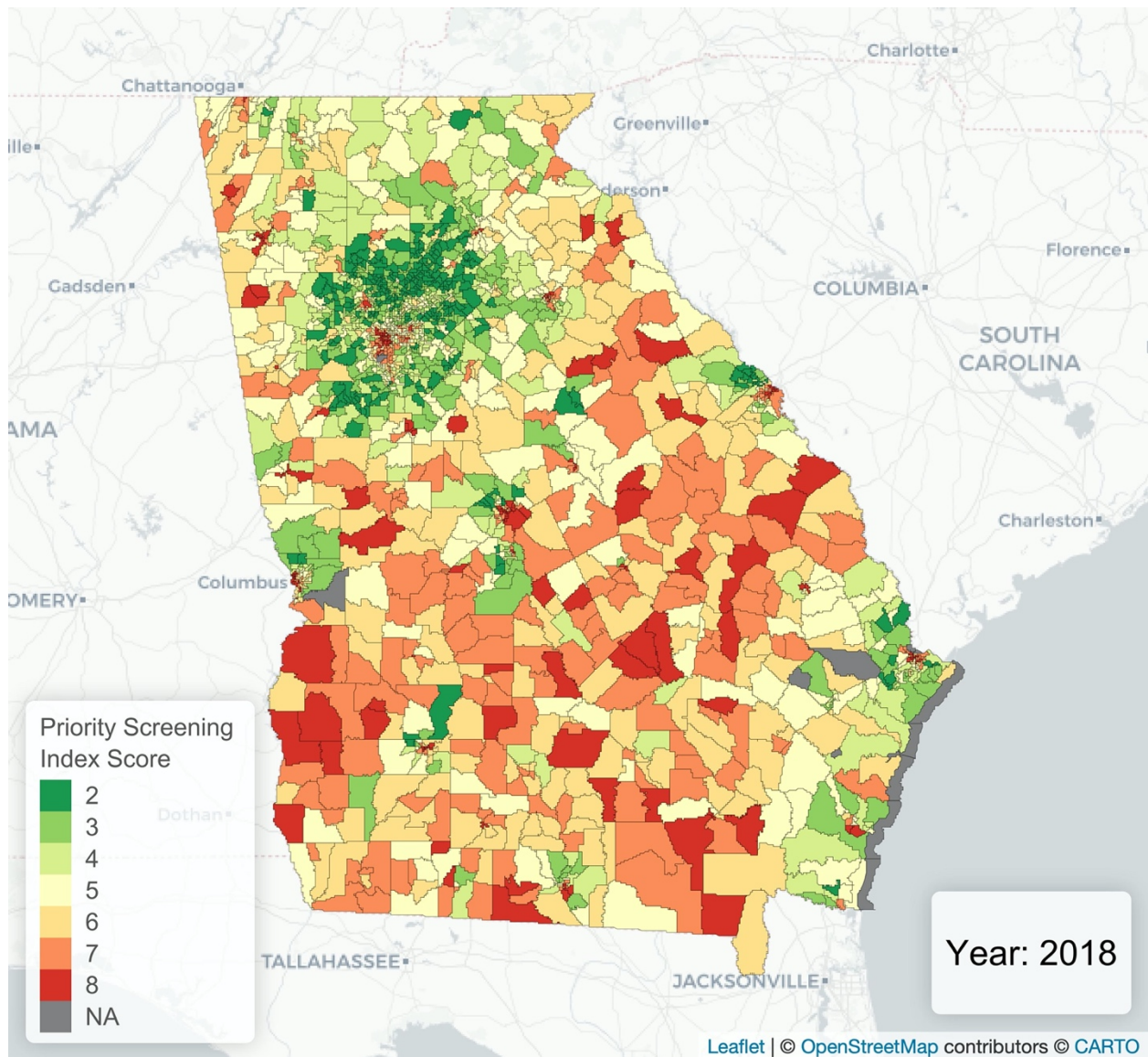

Figure 5: Priority Screening Index for Georgia Census Tracts when Georgia is the Reference Universe

DISCUSSION

Blood lead screening has generally been increasing in the Greater Atlanta area since 1998. However, as the CDC has stressed, effectively targeting those screening tests is crucial to identify the most children at risk of lead exposure (CDC, 1997b). The lack of significant association between ZIP code screening rates and the proportion of houses built before 1950 is concerning because the lead paint often found in older housing is a major source of lead exposure (CDC, 1997a; Reissman et al., 2002). This lack of association is especially troubling because it has persisted for years despite being highlighted by Vaidyanathan et al. (2009). In 2018, 16.5% of the total 517,488 housing units in the greater Atlanta area were built before 1950. Therefore, children in more than 85,000 houses could have increased risk for lead exposure without being effectively targeted for blood lead screening. Additionally, the linear regression model for screening rate with the highest adjusted R^2 included the proportion of people who are non-Hispanic black. The small but negative coefficient on this significant term is concerning as non-Hispanic black populations are associated with higher lead exposure and BLLs (Dixon et al., 2009; Jones et al., 2009; Raymond et al., 2014).

The most recent assessment of areas in Georgia with high lead exposure risk is the map of high-risk counties from Rustin et al. (2015). The counties highlighted in that paper have little correspondence with the counties identified as high risk by this priority screening index (see Figure S5). The Rustin et al. (2015) map may therefore not be capturing risk related to housing age and relative poverty. Instead, this prevalence-based map may reflect population size and screening rates more than an increased risk of exposure.

Focusing in on small geographic areas is important to identify those at risk for the more subtle low-level lead exposures facing children today. The priority screening index calculated

here focused on census tracts because they are a small geographic area with available census bureau data. As the hierarchical maps demonstrate, counties and ZIP codes with a low- or mid-level priority screening index value can contain smaller regions of high-priority areas that might not be targeted for screening under a county-level strategy.

The priority screening index for census tracts in the greater Atlanta area shows a cluster of high priority tracts in the westside of Atlanta. This area includes English Avenue and Vine City, historically black neighborhoods that have been highlighted in the media for incredibly high poverty and unemployment rates (Belson, 2017; Blau, 2018; Green, 2019). While this area was identified as high risk here based on housing age and relative poverty, industrial slag (another source of lead) has also been identified in that area (Balotin et al., 2020; Peters, 2019) This result is further strengthened by the consistently high index values assigned to these tracts when the index is applied to the state of Georgia and the entire nation. This easy way to run a preliminary check on the strength of results is a key advantage of this index for anyone who might implement it.

While easier to replicate and useful for targeting, analyzing BLLs and screening rates by geographic area is inherently less precise than analyzing address-level data. Here, data by individual screened children was not available due to HIPAA protections which limits the precision of this analysis. The lack of individual address data also prevented BLL and screening data from being aggregated to different geographic areas (other than ZIP codes and counties) so census tract level screening rates could not be assessed.

Similar to the housing data used by Vaidyanathan et al. (2009), the housing data used here did not have any information on lead remediation or other interventions to eliminate sources of lead. Older houses may no longer pose an exposure risk if they have been successfully treated

to remove lead so some areas with a high proportion of older houses may pose a lower risk than the priority screening index indicates. Additionally, housing age and all other demographic data were estimates from the ACS, but the variation around these estimates was not incorporated into the priority screening index. The ACS data only exist for ZIP codes from 2011 and 2018 which limited the years that could be included in some analyses. Finally, other sources of lead such as coal ash, air pollution, and contaminated food, soil, and water were not included in the priority screening index which limits its ability to capture lead exposure risk. These factors can also be major contributors to lead exposure and further work should be done to assess incorporating such sources into the priority screening indexes (ACCLPP, 2012; Liang et al., 2010; Mielke & Reagan, 1998).

There are many other opportunities for future work to continue to assess the risk of low-level lead exposure in Atlanta. First, analysis of address-level data could help build an understanding of blood lead screening rates. Using individual data, screening tests and results could be aggregated at the census tract level and the relationship between census tract screening rates and housing age and relative poverty could then be assessed. This higher resolution data would also allow for comparisons between census tract level priority screening index values and screening rates. These differences can then be used to identify specific under-screened census tracts to be targeted for increased screening (see Figure S6 for difference scores at the larger ZIP code level).

As more surveillance data about low-level lead exposure become available, it will also be important to continue to assess lead exposure risk factors. Identifying socioeconomic factors associated with low but elevated BLLs is crucial to help target blood lead screening. This work

could help validate this priority screening index or potentially highlight other factors besides housing age and relative poverty that should be incorporated into the index.

Effectively identifying children who are more likely to be exposed to lead is especially critical to end chronic lead exposure. Identifying these children may be difficult with lower public concern and a need for highly specific targeting. However, this work is crucial as the danger of lead exposure is far from over and the remaining risk of exposure is not equally distributed. To continue decades of work and end racial and socioeconomic disparities, public health officials need to focus more than ever on targeting specific high-risk areas for blood lead screening and eventual intervention.

REFERENCES

ACCLPP. (2012). *Low Level Lead Exposure Harms Children: A Renewed Call for Primary Prevention*. papers3://publication/uuid/192646DF-D0FF-4987-AF54-368F7236CDD8

Alexander, F. W., Clayton, B. E., & Delves, H. T. (1974). Mineral and trace-metal balances in children receiving normal and synthetic diets. *Quarterly Journal of Medicine*, *43*(1), 89–111. https://doi.org/10.1093/oxfordjournals.qjmed.a067380

ATSDR. (1999). *Toxicological Profile for Lead*.

ATSDR. (2019). Toxicological Profile for Lead (Draft for Public Comment). *ATSDR's Toxicological Profiles*, *May*. https://doi.org/10.1201/9781420061888_ch106

Balotin, L., Distler, S., Williams, A., Peters, S. J. W., Hunter, C. M., Theal, C., Frank, G., Alvarado, T., Hernandez, R., Hines, A., & Saikawa, E. (2020). Atlanta Residents' Knowledge Regarding Heavy Metal Exposures and Remediation in Urban Agriculture. *International Journal of Environmental Research and Public Health*, *17*(6), 2069. https://doi.org/10.3390/ijerph17062069

Belson, K. (2017). Building a Stadium, Rebuilding a Neighborhood. *The New York Times*. https://www.nytimes.com/2017/01/12/sports/football/atlanta-falcons-stadium-arthur-blank-neighborhood.html

Blau, M. (2018). The Redemptive Love of Chiliquila Ogletree. *The Bitter Southerner*. https://bittersoutherner.com/the-redemptive-love-of-chiliquila-ogletree/

Brody, D. J., Pirkle, J. L., Kramer, R. A., Flegal, K. M., Matte, T. D., Gunter, E. W., & Paschal, D. C. (1994). Blood Lead Levels in the US Population. *JAMA*, *272*(4), 277. https://doi.org/10.1001/jama.1994.03520040039038

Bureau of Labor Statistics. (2018). *Consumer Price Index Research Series Using Current*

Methods (CPI-U-RS). 1–4. https://www.bls.gov/cpi/research-series/home.htm

Caito, S., & Aschner, M. (2015). Neurotoxicity of metals. In *Handbook of Clinical Neurology* (Vol. 131). https://doi.org/10.1016/B978-0-444-62627-1.00011-1

CDC. (1991). *Preventing lead poisoning in young children: a statement by the Centers for Disease Control*. U.S. Department of Health and Human Services. https://doi.org/10.1016/S0022-3476(78)80923-8

CDC. (1997a). *Blood Lead Levels Keep Dropping; New Guidelines Recommended for Those Most Vulnerable*. https://www.cdc.gov/media/pressrel/lead.htm

CDC. (1997b). *Screening Young Children for Lead Poisoning: Guidance for State and Local Public Health Officials Centers for Disease Control and Prevention*. https://www.cdc.gov/nceh/lead/docs/cdc_13364_1997.pdf

CDC. (2013). Blood lead levels in children aged 1-5 years - United States, 1999-2010. *MMWR. Morbidity and Mortality Weekly Report*, *62*(13), 245–248. https://doi.org/10.15585/mmwr.mm6355a6

CPSC. (1996). *Consumer Product Safety Commission Staff Recommendations for Identifying and Controlling Lead Paint on Public Playground Equipment. Vol 70*(CPSC Document# 6006). http://www.state.nj.us/dca/divisions/dhcr/rec/pdf/recleadpaint.pdf

Dixon, S. L., Gaitens, J. M., Jacobs, D. E., Strauss, W., Nagaraja, J., Pivetz, T., Wilson, J. W., & Ashley, P. J. (2009). Exposure of U.S. Children to Residential Dust Lead, 1999–2004: II. The Contribution of Lead-Contaminated Dust to Children's Blood Lead Levels. *Environmental Health Perspectives*, *117*(3), 468–474. https://doi.org/10.1289/ehp.11918

EPA. (2013). Integrated Science Assessment (ISA) for Lead (Final Report, Jul 2013). *U.S. Environmental Protection Agency*.

https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=255721

Georgia DPH. (2016). *Lead Screening Guidelines for Children*. https://dph.georgia.gov/lead-screening-guidelines-children

Green, J. (2019). Five years after Mercedes-Benz Stadium broke ground, is Atlanta's Westside revival working? *Curbed Atlanta*. https://atlanta.curbed.com/atlanta-photo-essays/2019/1/31/18201601/super-bowl-liii-atlanta-gentrification-poverty-blank

Haley, V. B., & Talbot, T. O. (2004). Geographic Analysis of Blood Lead Levels in New York State Children Born 1994–1997. *Environmental Health Perspectives*, *112*(15), 1577–1582. https://doi.org/10.1289/ehp.7053

HUD. (2019). *HUD USPS ZIP Code Crosswalk Files*. https://www.huduser.gov/portal/datasets/usps_crosswalk.html

James, H. M., Hilburn, M. E., & Blair, J. A. (1985). Effects of Meals and Meal Times on Uptake of Lead from the Gastrointestinal Tract in Humans. *Human Toxicology*, *4*, 401–407.

Jones, R. L., Homa, D. M., Meyer, P. A., Brody, D. J., Caldwell, K. L., Pirkle, J. L., & Brown, M. J. (2009). Trends in blood lead levels and blood lead testing among US children aged 1 to 5 years, 1988 2004. *Pediatrics*, *123*(3). https://doi.org/10.1542/peds.2007-3608

Kaplowitz, S. A., Perlstadt, H., & Post, L. A. (2010). Comparing lead poisoning risk assessment methods: Census block group characteristics vs. zip codes as predictors. *Public Health Reports*, *125*(2), 234–245. https://doi.org/10.1177/003335491012500212

Kemper, A. R., Cohn, L. M., Fant, K. E., & Dombkowski, K. J. (2005). Blood Lead Testing Among Medicaid-Enrolled Children in Michigan. *Archives of Pediatrics & Adolescent Medicine*, *159*(7), 646. https://doi.org/10.1001/archpedi.159.7.646

Krieger, N., Chen, J. T., Waterman, P. D., Rehkopf, D. H., & Subramanian, S. V. (2003).

Race/Ethnicity, Gender, and Monitoring Socioeconomic Gradients in Health: A

Comparison of Area-Based Socioeconomic Measures—The Public Health Disparities

Geocoding Project. *American Journal of Public Health*, *93*(10), 1655–1671.

https://doi.org/10.2105/AJPH.93.10.1655

Lanphear, B. P., Rauch, S., Auinger, P., Allen, R. W., & Hornung, R. W. (2018). Low-level lead

exposure and mortality in US adults: a population-based cohort study. *The Lancet Public

Health*, *3*(4), e177–e184. https://doi.org/10.1016/S2468-2667(18)30025-2

Liang, F., Zhang, G., Tan, M., Yan, C., Li, X., Li, Y., Li, Y., Zhang, Y., & Shan, Z. (2010). Lead

in Children's Blood Is Mainly Caused by Coal-Fired Ash after Phasing out of Leaded

Gasoline in Shanghai. *Environmental Science & Technology*, *44*(12), 4760–4765.

https://doi.org/10.1021/es9039665

McCabe, E. B. (1979). Age and sensitivity to lead toxicity: a review. *Environmental Health

Perspectives*, *Vol. 29*(April), 29–33. https://doi.org/10.2307/3429042

McClure, L. F., Niles, J. K., & Kaufman, H. W. (2016). Blood Lead Levels in Young Children:

US, 2009-2015. *Journal of Pediatrics*, *175*, 173–181.

https://doi.org/10.1016/j.jpeds.2016.05.005

Mielke, H. W., & Reagan, P. L. (1998). Soil is an important pathway of human lead exposure.

Environmental Health Perspectives, *106*(SUPPL. 1), 217–229.

https://doi.org/10.2307/3433922

Peters, S. (2019). *The Environmental and Health Effects of Emerging Agricultural Techniques*.

Pirkle, J. L. (1994). The Decline in Blood Lead Levels in the United States. *Jama*, *272*(4), 284.

https://doi.org/10.1001/jama.1994.03520040046039

R Core Team. (2019). *R: A Language and Environment for Statistical Computing* (3.6.2). R

Foundation for Statistical Computing. https://www.r-project.org/

Raymond, J., Wheeler, W., Brown, M. J., & Centers for Disease Control. (2014). Lead screening and prevalence of blood lead levels in children aged 1-2 years--Child Blood Lead Surveillance System, United States, 2002-2010 and National Health and Nutrition Examination Survey, United States, 1999-2010. *Morbidity and Mortality Weekly Report. Surveillance Summaries (Washington, D.C. : 2002)*, *63 Suppl 2*(2), 36–42.

Reissman, D. B., Matte, T. D., Gurnitz, K. L., Kaufmann, R. B., & Leighton, J. (2002). Is Home Renovation or Repair a Risk Factor for Exposure to Lead Among Children Residing in New York City? *Journal of Urban Health: Bulletin of the New York Academy of Medicine*, *79*(4), 502–511. https://doi.org/10.1093/jurban/79.4.502

Reissman, D. B., Staley, F., Curtis, G. B., & Kaufmann, R. B. (2001). Use of geographic information system technology to aid health department decision making about childhood lead poisoning prevention activities. *Environmental Health Perspectives*, *109*(1), 89–94. https://doi.org/10.2307/3434926

Roberts, J. R., Hulsey, T. C., Curtis, G. B., & Reigart, J. R. (2003). Using geographic information systems to assess risk for elevated blood lead levels in children. *Public Health Reports*, *118*(3), 221–229. https://doi.org/10.1016/S0033-3549(04)50243-1

Sargent, J. D., Bailey, A., Simon, P., Blake, M., & Dalton, M. A. (1997). Census Tract Analysis of Lead Exposure in Rhode Island Children. *Environmental Research*, *74*(2), 159–168. https://doi.org/10.1006/enrs.1997.3755

Sargent, J. D., Brown, M. J., Freeman, J. L., Bailey, A., Goodman, D., & Freeman, D. H. (1995). Childhood lead poisoning in Massachusetts communities: Its association with sociodemographic and housing characteristics. *American Journal of Public Health*, *85*(4),

528–534. https://doi.org/10.2105/AJPH.85.4.528

US Census Bureau. (n.d.). *TIGER/Line Shapefiles*.

https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

US Census Bureau. (2018a). Using Dollar-Denominated Data. In *Understanding and Using American Community Survey Data*. United States Census Bureau (USCB).

US Census Bureau. (2018b). *ZIP Code Tabulation Areas (ZCTAs)*.

https://www.census.gov/programs-surveys/geography/guidance/geo-areas/zctas.html

US Public Health Service. (1971). The Surgeon General's Policy Statement on Medical Aspects of Childhood Lead Poisoning. In *Pediatrics* (Vol. 48, Issue 3). Public Health Service.

World Health Organization. (2010). Exposure to Lead: A major public health concern. *World Healh Organization*, 6. https://doi.org/10.1016/j.ecoenv.2011.12.007

Ziegler, E. E., Edwards, B. B., Jensen, R. L., Mahaffey, K. R., & Fomon, S. J. (1978). Absorption and retention of lead by infants. *Pediatric Research*, *12*(1), 29–34. https://doi.org/10.1203/00006450-197801000-00008
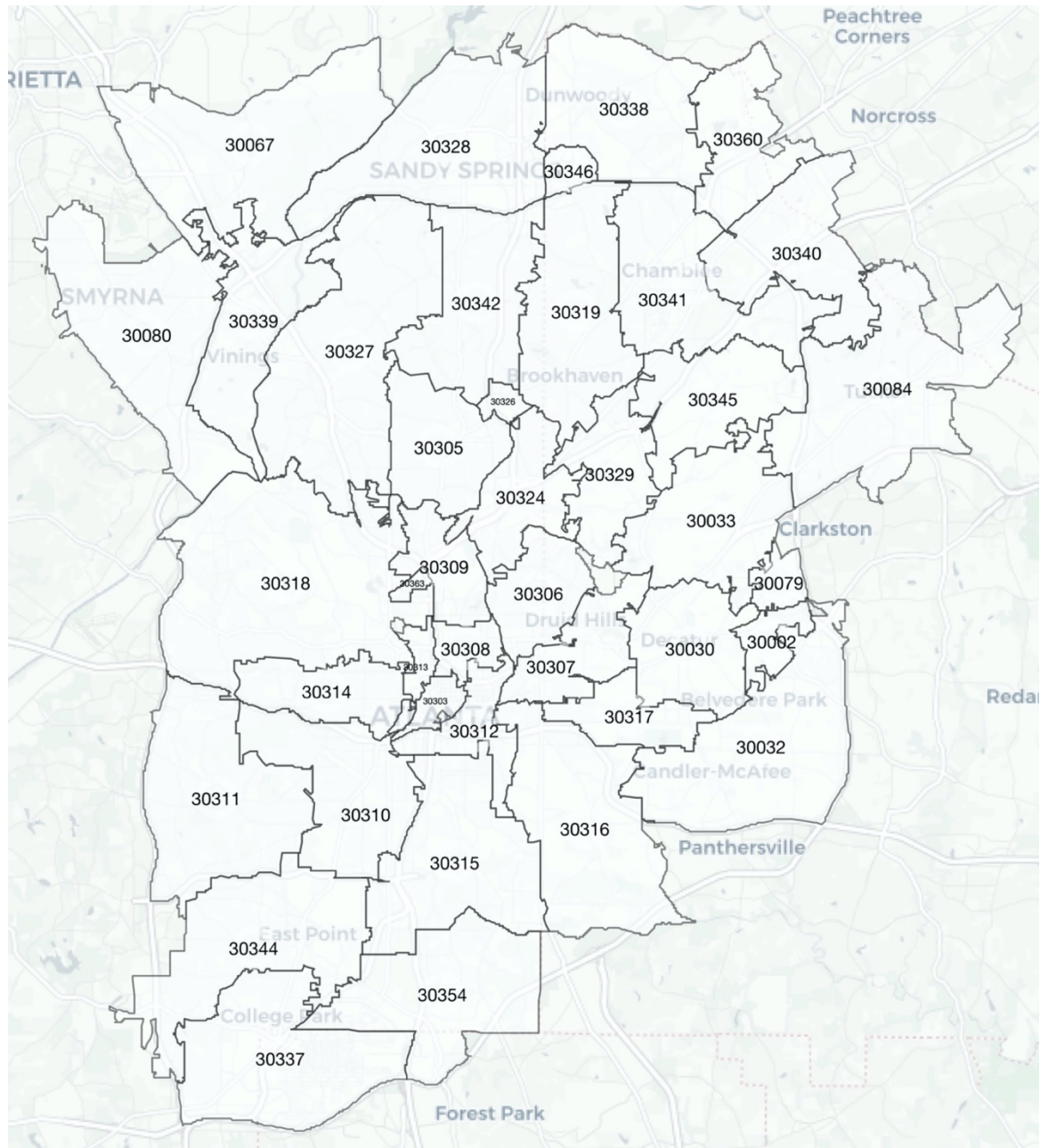
APPENDIX

Figure S1: Map of All ZIP Codes Defined as the Greater Atlanta Area

30002	30030	30032	30033	30067	30079	30080	30084	30303	30305	30306
30307	30308	30309	30310	30311	30312	30313	30314	30315	30316	30317
30318	30319	30324	30326	30327	30328	30329	30337	30338	30339	30340
30341	30342	30344	30345	30346	30354	30360	30363			

Table S1: ZIP Codes Defined as the Greater Atlanta Area
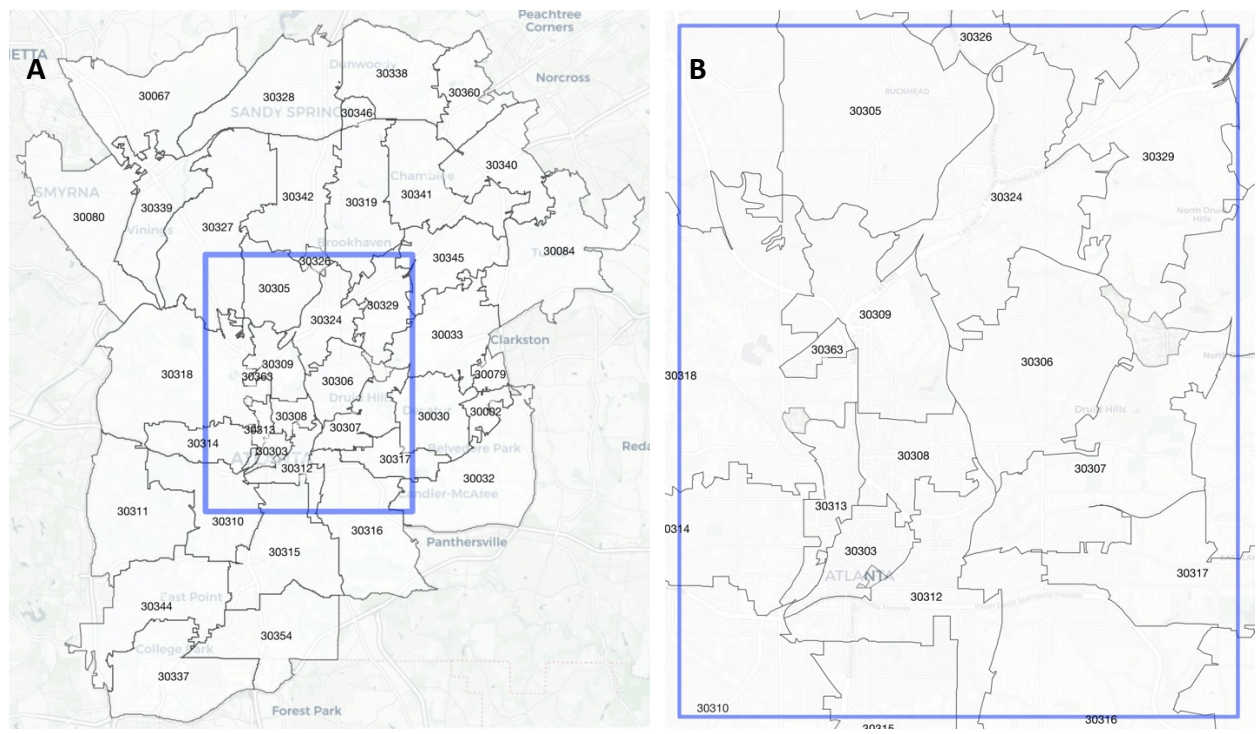
Figure S2: Map of (A) All ZIP Codes Defined as the Greater Atlanta Area and (B) a Close-Up View of ZIP Codes in Central Atlanta

Figure S3: Total Children Screened for Blood Lead in Georgia, 1998-2018
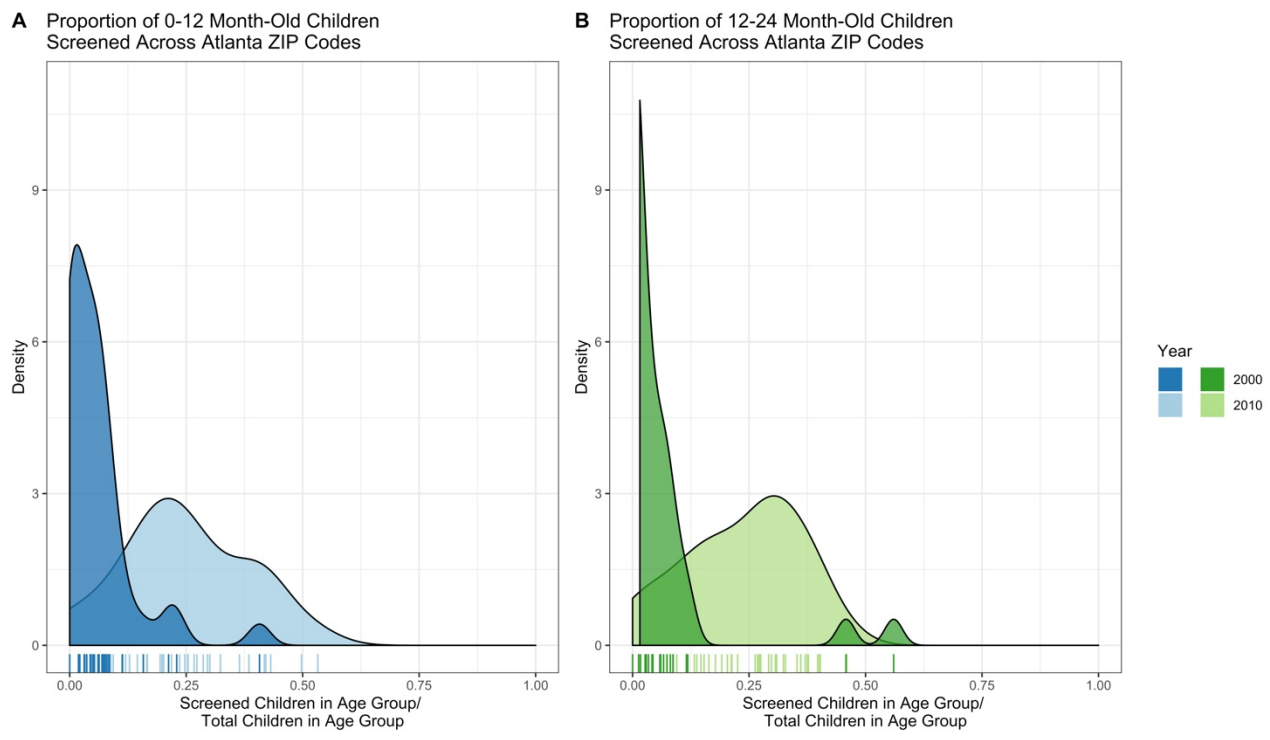
Figure S4: Raw Density Distribution of the Proportion of Children Screened in 2000 and 2010 for (A) 0-12 Month-Olds and (B) 12-24 Month-Olds
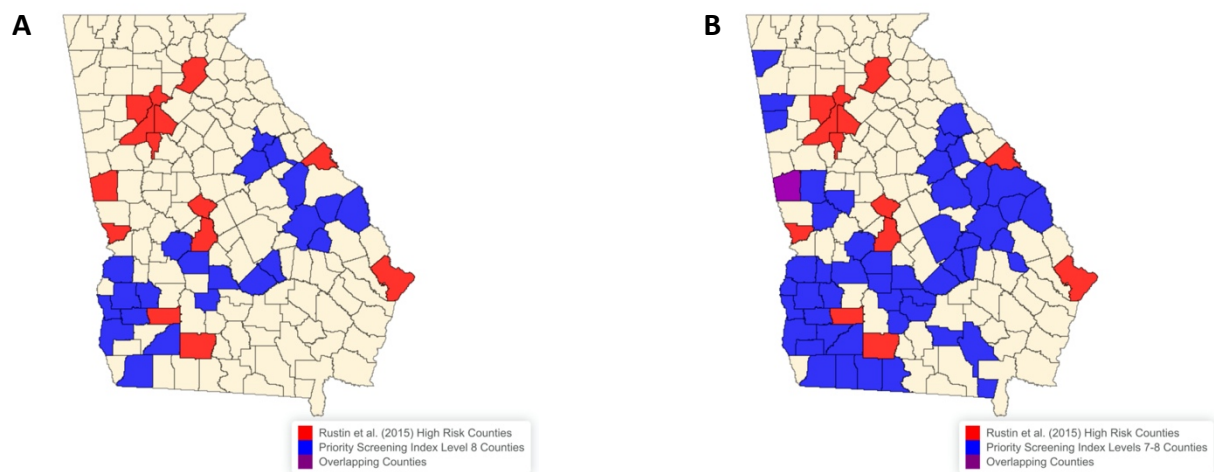

Figure S5: Comparison of Counties Identified as "High Risk" by Rustin et al. (2015) and Counties Identified By the Priority Screening Index as (A) Level 8 and (B) Levels 7 and 8 When Georgia is the Reference Universe
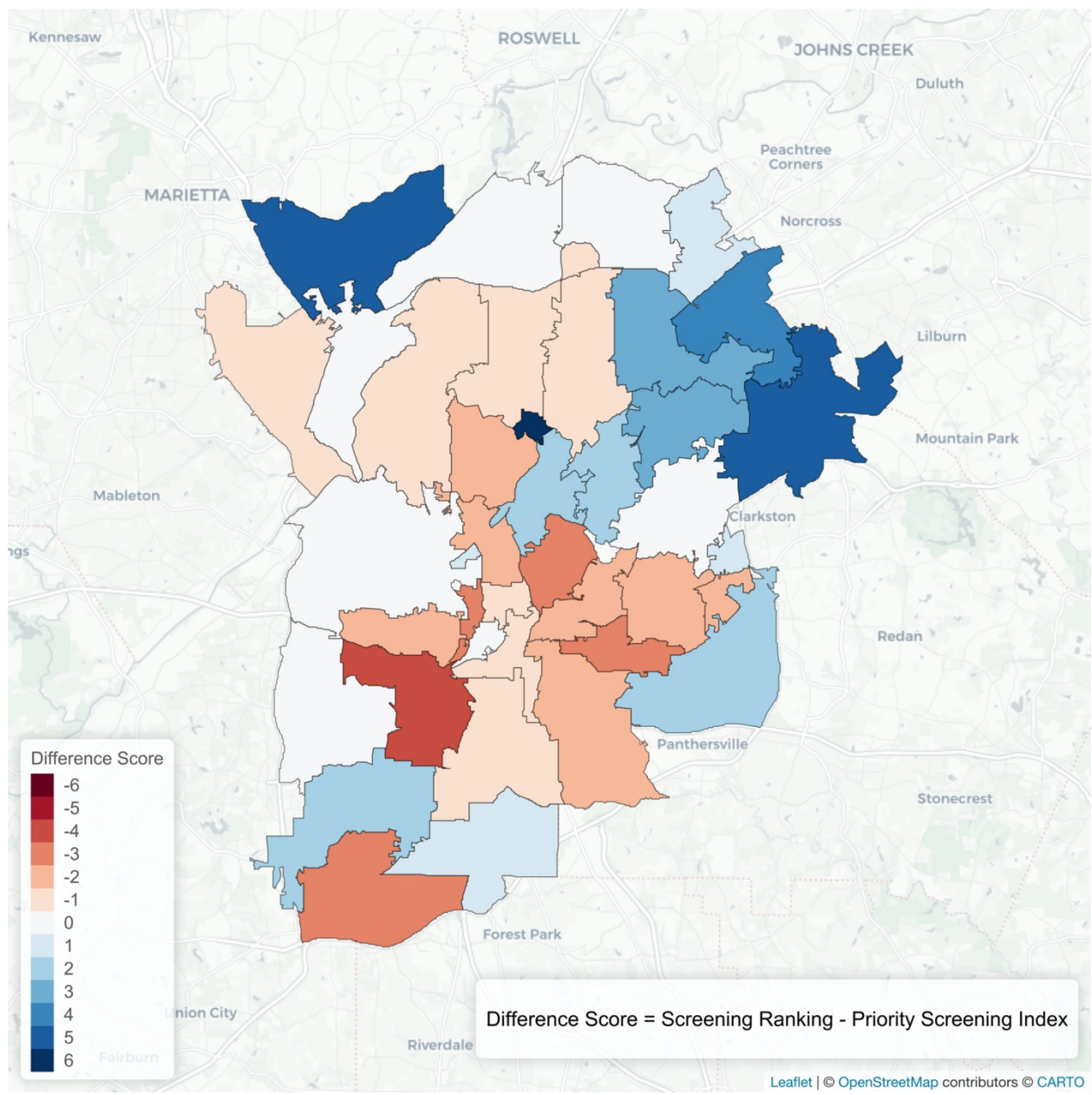
Figure S6: Greater Atlanta Area ZIP Codes Difference Scores