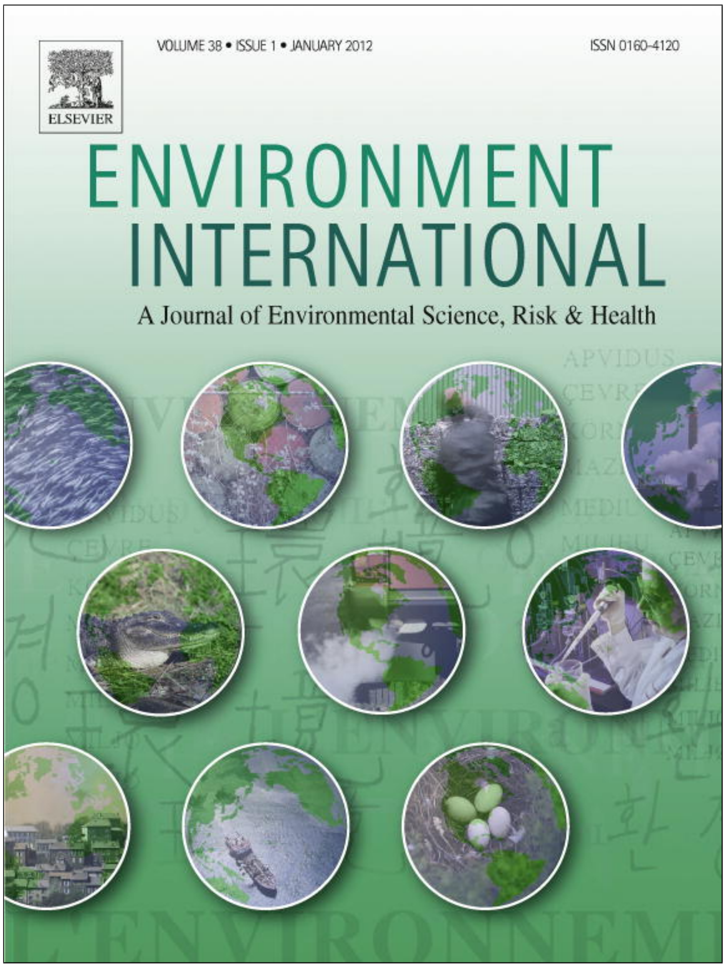

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The urban rise and fall of air lead (Pb) and the latent surge and retreat of societal violence

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ABSTRACT

We evaluate air Pb emissions and latent aggravated assault behavior at the scale of the city. We accomplish this by regressing annual Federal Bureau of Investigation aggravated assault rate records against the rise and fall of annual vehicle Pb emissions in Chicago (Illinois), Indianapolis (Indiana), Minneapolis (Minnesota), San Diego (California), Atlanta (Georgia), and New Orleans (Louisiana). Other things held equal, a 1% increase in tonnages of air Pb released 22 years prior raises the present period aggravated assault rate by 0.46% (95% CI, 0.28 to 0.64). Overall our model explains 90% of the variation in aggravated assault across the cities examined. In the case of New Orleans, 85% of temporal variation in the aggravated assault rate is explained by the annual rise and fall of air Pb (total = 10,179 metric tons) released on the population of New Orleans 22 years earlier. For every metric ton of Pb released 22 years prior, a latent increase of 1.59 (95% CI, 1.36 to 1.83, $p<0.001$) aggravated assaults per 100,000 were reported. Vehicles consuming fuel containing Pb additives contributed much larger quantities of Pb dust than generally recognized. Our findings along with others predict that prevention of children's lead exposure from lead dust now will realize numerous societal benefits two decades into the future, including lower rates of aggravated assault.

> "Sometime in the near future it probably will be shown that the older urban areas of the United States have been rendered more or less uninhabitable by the millions of tons of poisonous industrial lead residues that have accumulated in cities during the past century (Patterson, 1980)."

1. Introduction

After decades of steady increases in violent crime rates in the United States, the rates began to fall during the mid-1990s, declining 3–4% per year until 2010 when a larger than expected 13% decline was reported (Federal Bureau of Investigation, 2010; U.S. Department of Justice, 2010). Criminologists failed to predict the sudden decline in violent crime, with some forecasts of the period anticipating a surge not a retreat in crime rates (Fox, 1996). Ex post statistical models explain the observed decline in crime rates with rising rates of incarceration and police density, and even the legalization of abortion in the 1970s (Levitt, 2004). While these statistical models perform decently in the United States, they inadequately account for the trends of crime rates in other developed economies. For example, rates of violent crime increased in the 1990s across Europe and Oceania, precisely as incarceration rates and police per capita increased (Nevin, 2007).

More recently, an intriguing *environmental hypothesis* has been advanced to account for the unexpected decline in violent crime rates. The *environmental hypothesis* is similar to the *neurotoxicity hypothesis*, which is more specific in its hypothesis that exposure to Pb alters neurotransmitter and hormonal systems and may thereby generate aggressive and violent behavior (Stretesky and Lynch, 2001, 2004). Both hypotheses rest on two propositions. First, that the cognitive and behavioral traits of impulsivity, aggression, and low cognitive IQ are statistically associated with criminality and anti-social behavior, known as *self-control theory* in criminology (Gottredson and Hirschi, 1990). On the specific trait of low cognitive IQ, Gottfredson (1998) observes that "no other trait or circumstance yet studied is so deeply implicated in the nexus of bad social outcomes." The empirical status of self-control theory is well established, with a meta-analysis of 21 cross-sectional and longitudinal studies concluding that *low self-control* is among the most important predictors of criminal behavior (Pratt and Cullen, 2000). And secondly, that the possession of the behavioral and cognitive traits of *low self-control* increases

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significantly with childhood exposure to lead (Elliott, 1992; Needleman et al., 2002). On the Pb exposure-cognitive IQ nexus, Needleman (1990, p 86) writes: “The demonstrated effect size (difference between means of exposed and unexposed groups) in many studies is about 4 to 6 [IQ] points…. We have shown that a shift of this magnitude predicts a 4-fold increase in the rate of severely impaired children (IQ<80).” In addition to depressed IQ, lead poisoned children, as measured by the accumulation of Pb in their bones, have profound impulse control problems, as reflected in higher rates of juvenile delinquency and adjudication (Needleman et al., 2002). The Cincinnati Lead Study prospective longitudinal assessment of serial blood Pb determinations also found an association between of early childhood Pb exposure and antisocial acts by adolescents (Dietrich et al., 2001).

Lead is a neurotoxin with lasting neuroanatomical and behavioral effects on exposed children (Olympio et al., 2009). Magnetic Resonance Imaging (MRI) shows that adults who were lead poisoned as children have significantly reduced gray matter volume as compared to adults not lead poisoned as children (Cecil et al., 2008, 2011). Lead-associated volumetric loss of gray matter is most visible in the prefrontal cortex and anterior cingulate cortex, regions of the brain known to govern mood regulation, executive control, and judgment.

Combining these claims, the environmental hypothesis holds *that present period rates of adult violence are associated with spatial and temporal variation in childhood Pb exposure, linked together by the behavioral and cognitive mechanisms of impulsivity, aggressivity, and depressed IQ*. Nevin (2007) tested the logic of this environmental hypothesis by analyzing national arrest rates for violent crime in the United States, Britain, Canada, France, Australia, Finland, Italy, West Germany, and New Zealand as a function of pre-school Pb exposure observed in these nations. His nation-specific regression models accounted for 63–95% of temporal variation in arrest rates, with Nevin (2007, p 333) concluding that: “The association between crime and preschool blood lead should lend urgency to global efforts to eliminate preschool lead exposure.” Similarly, Ryes (2007) observed that the sharp state-specific reductions in lead emissions *22 years prior* resulting from the removal of lead in gasoline are responsible for 56% of the decline in U.S. state-specific violent crimes in the 1990s. Finally, Stretesky and Lynch (2001, 2004) suggested the same reduction in homicides and crime at the scale of U.S. counties. While these ecological studies are compelling, the levels of statistical aggregation – nation, U.S. states and counties – are theoretically problematic, as the risk of exposure to lead aerosols operates at finer scales (Mielke et al., 2011a).

Instead of evaluating the crime effects of Pb exposure at the scale of nations, U.S. states or counties, our study exploits air Pb data at the city-scale (Mielke et al., 2010, 2011a). We evaluate annual air lead emission estimates for Chicago (Illinois), Indianapolis (Indiana), Minneapolis (Minnesota), San Diego (California), Atlanta (Georgia), and New Orleans (Louisiana) in combination with annual FBI records on aggravated assault rates for the same cities. Fig. 1 is a map of the locations of the cities included in this study. After evaluating six cities that differ in size, climate, and socioeconomic characteristics, we then consider the findings as they pertain to New Orleans where an extensive literature exists on environmental lead, children's exposure and health outcomes (e.g. Mielke et al., 1997; Rabito et al., 2012; Zahran et al., 2010, 2011).

2. Methods

This study is an ecological analysis that includes both response and predictor variables which are analyzed using a *least squares dummy variable* (*LSDV*) *regression* procedure.

2.1. Response variable

As a test of the environmental hypothesis, aggravated assault is a theoretically appropriate violent crime to analyze because unlike the violent crimes of murder, robbery, and rape (that require more planning and forethought), aggravated assault is characterized by impulsive aggression. While there is a sizeable literature in criminology noting that impulsivity is involved in acts of homicide, robbery, and

Fig. 1. Map of the locations of cities evaluated for this study. Note that the cities are located in a wide range of climatic and geographic settings.

rape (see Jacobs, 2000; Wright and Decker, 1997), and that aggravated assaults can be premeditated, we focus our investigation on assault crimes because a weapon is typically involved in acts of robbery and murder, implying a level of premeditation that is less typical in acts of assault. While "weapon use in causing harm has typically been thought of as a premeditated, planned behavior" (Brennan and Moore, 2009: 219), scholars note that impulsive weapon use is a plausible notion deserving of more scientific investigation.

The Uniform Crime Reporting program defines aggravated assault as "*an unlawful attack by one person upon another for the purpose of inflicting severe or aggravated bodily injury* (Levitt, 1998)." Instead of analyzing *arrest rates* (Nevin, 2007), that more likely reflect the efficacy of law enforcement than the level of local crime (Levitt, 1998), we analyze *reported* aggravated assaults to police. The rate is therefore calculated as the number of reported aggravated assaults divided by population size and multiplied by 100,000. Aggravated assault rate data from 1972 to 2007 was obtained from the Bureau of Justice Statistics (Federal Bureau of Investigation, 2000, 2011).

2.2. Predictor variables

Annual city estimates (1950–1985) of air Pb from vehicle traffic in metric tons (mT) were calculated from data on state gasoline usage, city traffic volume, average miles per gallon, the amount of lead per gallon of different grades of fuel (regular leaded and unleaded, premium leaded and unleaded), and EPA fate of lead in the vehicle engine and exhaust (for detail see Mielke et al., 2010, 2011a). Note that the data from Mielke et al. (2011a) was extended by applying the Pb regulation of 1.1 g/gal set in 1982 to the leaded gasoline consumption from 1982 to 1985 (U.S. EPA, 1985). Selected cities vary considerably in the amount of air Pb from vehicle traffic over the calculation period of 1950–1985: Chicago (66,698 mT), Indianapolis (16,803 mT), Minneapolis (27,387 mT), San Diego (25,875 mT), Atlanta (33,161 mT), and New Orleans (10,179 mT). To capture the known lag between childhood Pb exposure and adult criminality, we follow Ryes (2007) and forward lag air Pb emissions by 22 years.

While the 22 year forward lag used in our investigation is both statistically optimal and motivated by Ryes' (2007) analysis of reported crimes at the state level, other studies use different forward lag values. Nevin (2007), for instance, in his cross-national analysis of arrest rates, deployed a 19 year forward lag. Determining the optimal forward lag is an open question. Theoretically, the optimal lag ought to fall somewhere in what criminologists call the age–crime curve (Blumstein, 1995), an interval between 15 and 24 years of age. The precise peak within the age–crime curve, and the corresponding optimal forward lag in investigations of Pb exposure and violent crime, may be calculable a priori from the type of violent crime (assault, robbery, or homicide), the type of rate (arrest rates, reported crime rates, or victimization survey data), the time period, and the country being analyzed.

In addition to air Pb, statistical analyses include control variables measuring city income and demographic characteristics. *Income per capita* is measured as the aggregate income of a city divided by the total population, and annual income data are from the Bureau of Economic Analysis (1972–2005). Because age-specific arrest rates for aggravated assault have a historically persistent structure, with the vast majority of persons arrested for aggravated assault falling between 15 and 24 years of age (Cohen and Land, 1987; Quetelet,

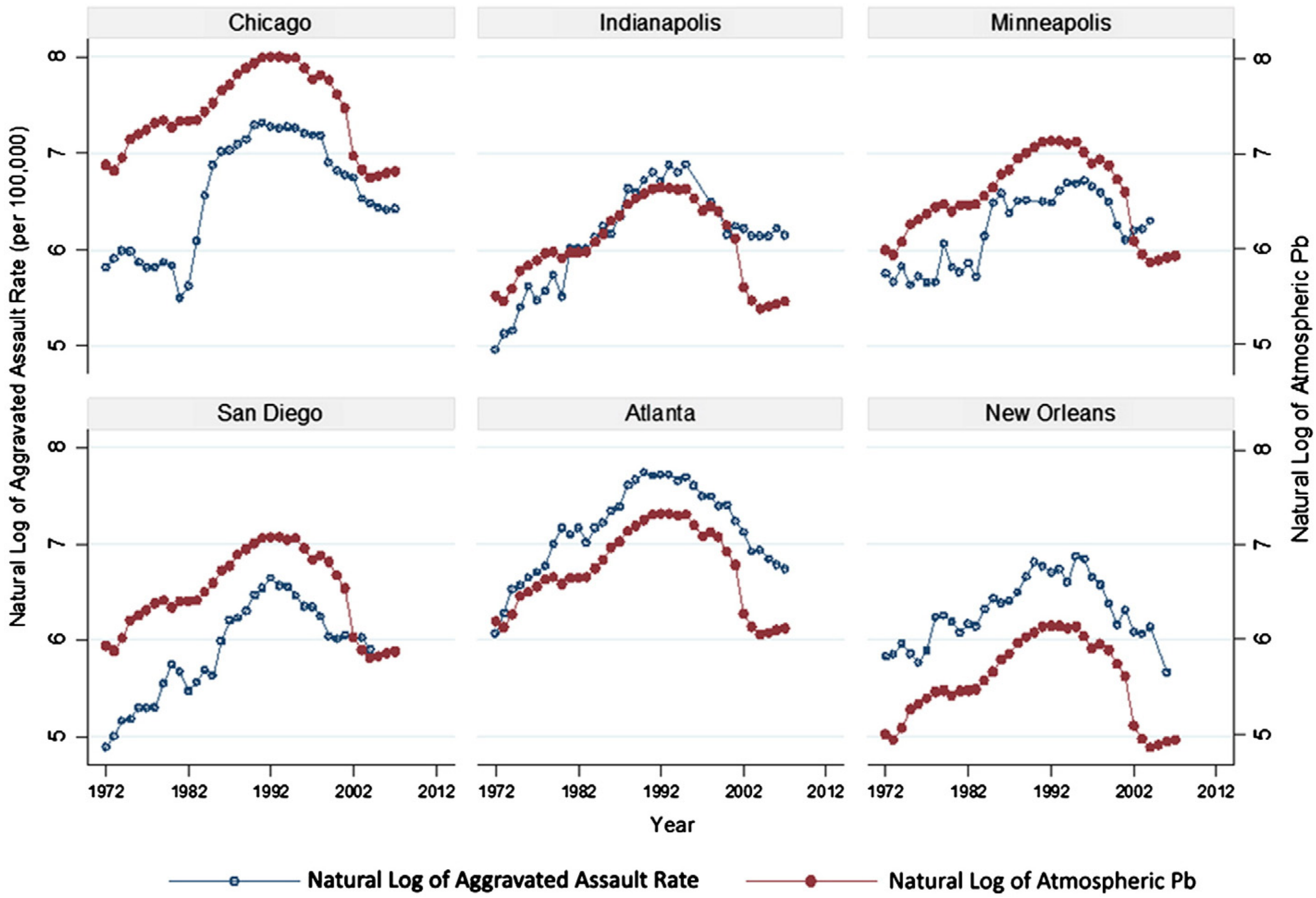

Fig. 2. Six panels showing two series of data, the estimated metric tons of air Pb in each metropolitan area (Y_1 axis) and the aggravated assault rate for adults as reported to the FBI by police departments in each city (Y_2 axis).

1984), we calculated the percentage of *population between 15 and 24 years of age*. Age structure by year data is from the National Cancer Center Institute (1972–2005).

2.3. Statistical model

We analyze temporal variation in aggravated assault rates (y) with a *least squares dummy variable* (*LSDV*) *regression* procedure. Allowing i to denote city and t to denote year of observation, and y_{it} the aggravated assault rate of city i in year t, our regression model is:

$$y_{it} = \beta_0 + \beta_1 L_{it-22} + \beta_2 I_{it} + \beta_3 A_{it} + \beta_4 T_{it} + \beta_5 T_{it}^2 + \Gamma_1 D_i + e_{it} \tag{1}$$

where, β_0 is the average aggravated assault rate for our reference city *Atlanta*, and L_{it-22} is the air lead level in an observed city 22 years prior, I_{it} is the income per capita in a city, A_{it} is the percentage of city population in the peak period of the age–crime curve (i.e.,15–24 years old), T_{it} and T_{it}^2 represent a time quadratic to account for the known parabolic shape of aggravated assault in time, D_i represents a set of dummy variables corresponding to each city, and e_{it} is the residual term with assumed random structure.

3. Results

We begin with a graphical presentation of the association between aggravated assault and air Pb. Fig. 2 displays six panels showing two series of data for each city, including the annual estimated metric tons of air Pb shifted forward by 22 years for each metropolitan area (Y_1 axis) and the annual aggravated assault rate for adults reported to the FBI by police departments of each city (Y_2 axis). Time is on the horizontal axis, moving annually. Because of the 22 year forward lag in air Pb emissions, the year 1972 for instance, corresponds to the observed aggravated assault rate in 1972, and the metric tons of air Pb from vehicle traffic observed in 1950. For ease of readability across panels, both *y-axes* are log transformed. All panel series behave relatively similarly in terms of angle function, amplitude and wave length.

In Table 1 we report a series of regression models. We log transform the aggravated assault rate and relevant covariates. Interpretation of reported coefficient is in percentage terms. Our air Pb variable behaves robustly across model specifications. We concentrate our interpretation on fully saturated model 4. Adjusting for income, demographic, and time variables, we find that a 1% increase in air Pb emissions 22 years prior increases the present period expected aggravated assault rate by 0.46% (95% CI, 0.28 to 0.64). The 22 year lag effect in atmospheric Pb is not only statistically optimal, but theoretically consistent with the behavior of the age–crime curve. Recall, adult propensity to commit an act of violence peaks between 15 and 24 years of age. Overall, our full model explains 90% of the variation in aggravated assault across cities examined.

Next, we focus our analysis on New Orleans, where lead exposure of children is known to be particularly high (Mielke et al., 1997; Zahran et al., 2011). Fig. 3 displays the annual data of the two series on the X axis for New Orleans, indicating the estimated metric tons of air Pb area (Y_1 axis) and the aggravated assault rate for adults (Y_2 axis) as reported to the FBI by the New Orleans police. Again, we observe two curves of similar mathematical properties. Fig. 4 is a scatter-plot of the relationship between air Pb and the latent 22 year aggravated assault rate showing a remarkably strong statistical association for the best fit linear solution ($r^2 = 0.853$, $p < 0.001$). Fig. 5 shows the same scatter-plot for the cities of Chicago, Indianapolis, Minneapolis, San Diego, and Atlanta. Model fit statistics behave similarly across these cities.

The strong association between air Pb and aggravated assault rate provides insight into latent behavioral outcomes resulting from environmental lead exposures by children who were subjected to lead dust during their most sensitive developmental years.

Table 1
Least squares regression coefficients predicting aggravated assault rates in selected cities, 1972–2007.

	Model 1	Model 2	Model 3	Model 4
Air Pb	0.468*** (0.0443)	0.585*** (0.0633)	0.600*** (0.0745)	0.458*** (0.0927)
Income per capita		−3.211*** (0.485)		−0.767**(0.358)
Percent 15–24 age		0.120 (0.467)		−0.313 (0.343)
Time		0.388*** (0.0404)	0.0557*** (0.0138)	0.160*** (0.0386)
Time^2		−0.00494*** (0.000453)	−0.000925** (0.000372)	−0.00264*** (0.000643)
Chicago			−1.004*** (0.0873)	−0.864*** (0.0920)
Indianapolis			−0.611*** (0.0650)	−0.747*** (0.0834)
Minneapolis			−0.852*** (0.0444)	−0.824*** (0.0606)
San Diego			−1.133*** (0.0385)	−1.134*** (0.0367)
New Orleans			−0.155 (0.104)	−0.437*** (0.139)
Constant	3.340*** (0.285)	28.62*** (3.107)	2.498*** (0.426)	10.68*** (2.748)
R^2	0.291	0.635	0.895	0.903
F	111.94	71.04	320.03	305.97
N	205	198	205	198

Robust errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

4. Discussion

4.1. Limitations

While our results are consistent with individual-level theoretical expectations, it is important to stress that by design this is an ecological analysis and not an observation of individuals. It is also important to note that both migration behavior and sub-city spatial variation in Pb exposure add uncertainty to the results. Nevertheless, the statistical results are sufficiently strong to warrant deeper investigation.

4.2. Lead additives

The rise and fall of lead additive use is well-known (Nriagu, 1990). The 1950–1972 increase of lead additives coincided with the development of the massive federal highway construction program and the consequent increase of vehicle miles driven by automobiles with low fuel efficiency. The phase-down of lead additives began in 1972 with the introduction of air pollution controlling catalytic converters that required unleaded fuel. On January 1, 1986, an especially large phase-down of lead occurred following a Senate Hearing in 1984 that was requested by Minnesota citizens and the Minnesota Legislature who petitioned Congress for a federal ban on leaded gasoline (Airborne Lead Reduction Act of 1984; Comments by the Minnesota Lead Coalition, 1984; U.S. EPA, 1985). The human health response to the reduction of air lead after the January 1, 1986 rapid phase-down of tetra-ethyl Pb as fuel additives was indicated by the 90% decline of children's blood lead of children that occurred between 1976–1980 and 1988–1991, i.e., before and after the rapid phase-down (Mahaffey et al., 1982; Meyer et al., 2003). Associated with lead exposure rates the results of our study indicate that environmental air Pb emissions had measurable impacts on aggravated assault rates of adult citizens who were children from 1950 through the 1980s. According to the logic indicated by the results of this study, the unexpected 13% decrease in aggravated assault rates reported in

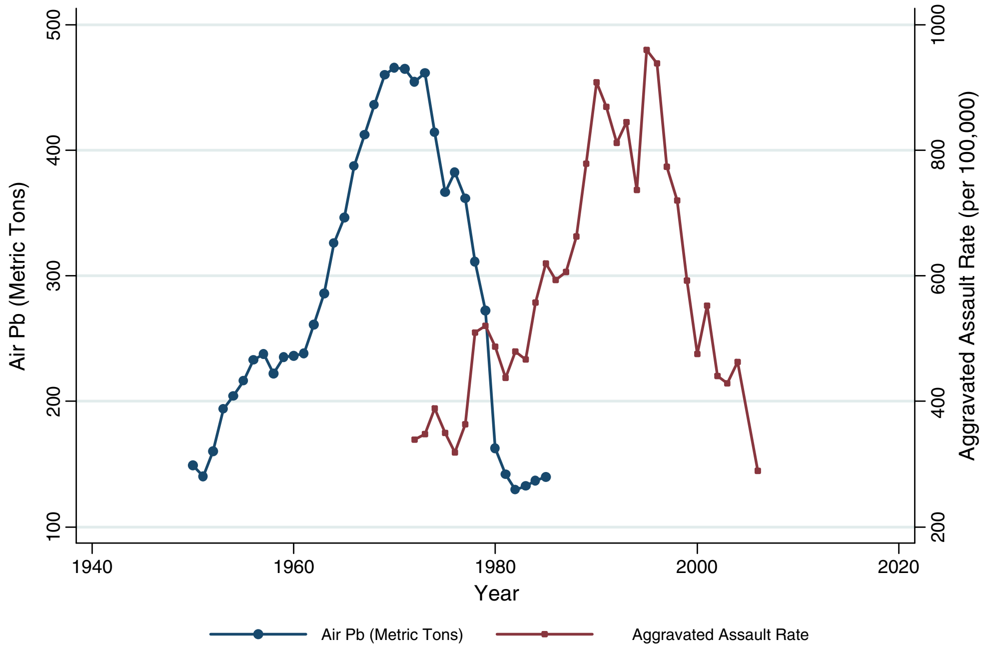

Fig. 3. The data of two series on the X axis for New Orleans, Y_1 axis indicating the annual incremental increases and decreases of atmospheric Pb emissions (total = 10,179 mT) and the Y_2 axis showing the annual aggravated assault rate as reported to the FBI by the New Orleans police.

2010 (U.S. Department of Justice, 2010) is probably the outcome of the rapid phase-down of leaded gasoline that began on January 1, 1986. A follow-up FBI report indicates a continuation of the rapid decline in aggravated assault rates during the first half of 2011 (Federal Bureau of Investigation, 2011).

The relationship between air Pb and aggravated assault is not a statistical aberration, nor can it be explained away by other common factors such as changing age structure (Levitt, 1999). Stretesky and Lynch (2001, 2004) projected the relationship for the scale of the U.S. county. Here the relationship is refined as a result of a new dataset that made it possible to extend the relationship to the scale of the city (Mielke et al., 2010, 2011c). Overall, between 66% (Minneapolis) and 90% (Atlanta) of the temporal variation of aggravated assault is explained by the tonnages of air Pb released in cities 22 years earlier. In the case of New Orleans, 85% of temporal variation in the aggravated assault rate is explained by the tonnages of air Pb released on the population of New Orleans 22 years earlier; for every metric ton of Pb released 22 years prior, a latent increase of 1.59 (95% CI, 1.36 to 1.83, $p<0.001$) aggravated assaults per 100,000 were reported to police. A 1% increase in air Pb 22 years prior induced a 0.8% increase in the latent period aggravated assault rate. Such predictive power is rarely

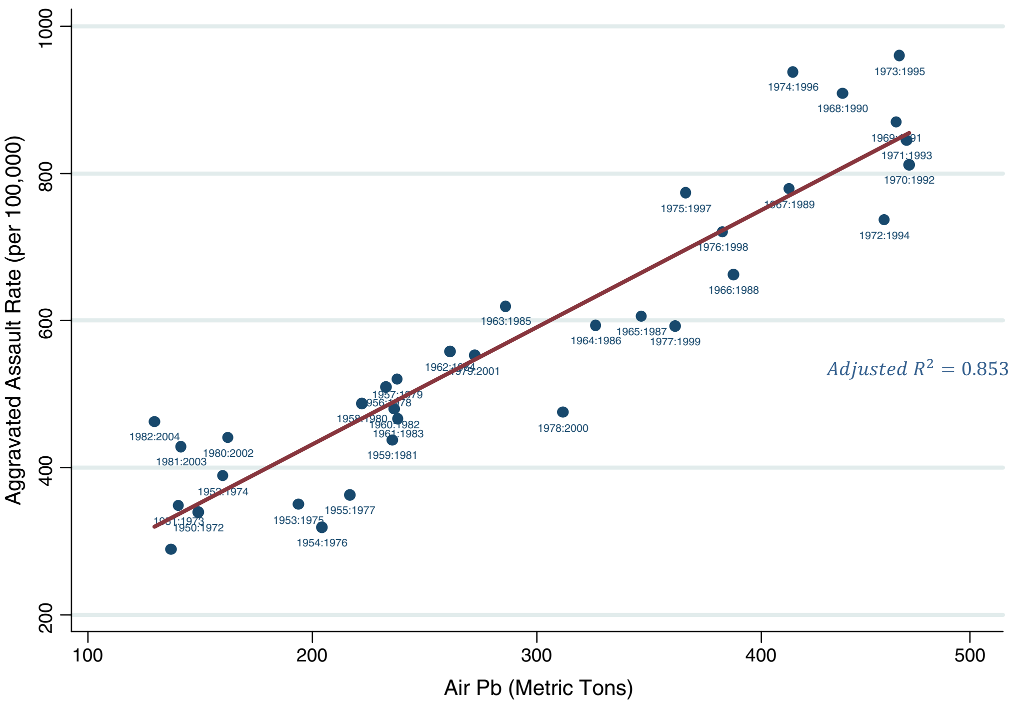

Fig. 4. A scatter-plot of the relationship between air Pb and the latent 22 year aggravated assault rate in New Orleans showing the best fit linear solution ($r^2 = 0.853$, $p<0.001$).

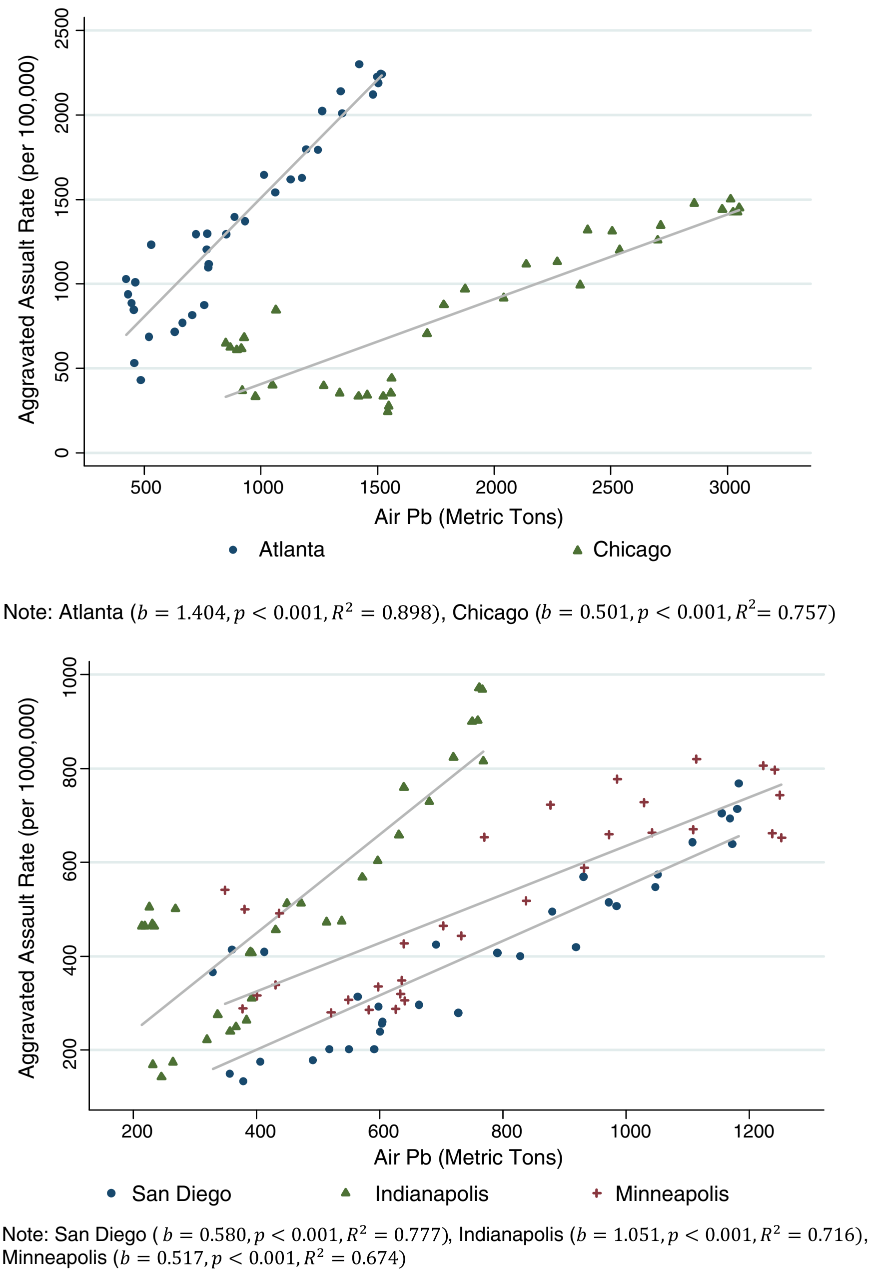

Fig. 5. A scatter-plot of the relationships between air Pb and the latent 22 year aggravated assault rate across cities showing the best fit linear solution.

observed in social science data of this kind, particularly in statistical models with one variable.

4.3. The costs of lead dust exposure in New Orleans

In New Orleans, children residing in homes with lead-based paint and/or living in lead-dust contaminated communities are at high risk of lead poisoning (Copeland, 2012; Mielke et al., 2011b; Rabito et al., 2012). Estimated quantities of lead dust distributed and settled within urban communities by vehicles fueled with leaded gasoline exceeds the quantities of lead dust estimated from the total removal of exterior lead-based paint (Mielke and Reagan, 1998; Mielke et al., 2001, 2011b). In New Orleans, the estimated quantity of air Pb emitted by vehicles from 1950 to 1985 is 10,179 mT. Assuming generously that all exterior paint used in the period contained 25.7% Pb, that the average surface area of a home is ~370 m^2 (4000 ft^2), and that all 86,000 old homes were power-sanded to bare wood, then in the worst case scenario the total potential amount of lead-dust introduced into the environment would be 1811 mT (Mielke et al., 2011b). Legacy Pb dust can be measured and mapped by systematically collecting and analyzing soil samples throughout the city (Abel et al., 2010; Mielke et al., 2005).

Soil is an active reservoir of Pb dust especially during late summer and fall when contaminated soil is re-entrained air Pb also increases (Laidlaw et al., 2011). The seasonal flux of soil Pb re-entrainment is reflected in the seasonal flux of children's blood Pb (Laidlaw et al., 2005). In New Orleans, environmental lead is distributed unevenly in the city. High environmental lead levels are disproportionately found in poorer inner-city communities of color with high public housing density (Campanella and Mielke, 2008). Neighborhoods with high levels of environmental lead are home to higher fractions of children with blood Pb >10 μg/dL (Mielke et al., 1997, 1999, 2007, 2011b; Zahran et al., 2011). Schools in New Orleans with higher fractions of children with blood Pb >10 μg/dL perform significantly worse on Louisiana Educational Assessment Program test scores (Zahran et al., 2009). Consistent with results reported in this manuscript, violent crimes in New Orleans cluster spatially in lead contaminated neighborhoods (Lowry et al., 1988).

The costs of lead exposure are exceedingly high for society. From a global perspective the benefits resulting from the phase-out of leaded fuel have been estimated at 2.45 trillion dollars/year (Tsai and Hatfield, 2011). In New Orleans, large costs for Pb exposure continue. For example, in 2003 the city of New Orleans paid an estimated $42 million to cover incarceration costs (Spatial Information Design Lab, 2007). These costs do not take into account extra police force expenses or other costs related to maintaining public safety, nor do they account direct costs imposed on victims, families, and communities harmed by violence (McCarthy, 2011). Our statistical results suggest that one way to limit the future costs of adult violence is to minimize present period exposure of children to environmental Pb.

Curtailing Pb exposure must include cessation of Pb dust from power sanding lead-based paints during renovation (Mielke et al., 2001; Rabito et al., 2012). In addition, remedial actions are being directed toward children's play areas in parks, childcare centers and public housing developments (Copeland, 2012; Mielke et al., 2011c; Reckdahl, 2011; Schleifstein, 2011), and these projects must be extended to private properties (Mielke et al., 2001; Rabito et al., 2012). The ability by New Orleans to change its environment is related to the availability of a massive resource of low Pb alluvial soil (median of 5 mg/kg) originating as Mississippi River sediments (Mielke et al., 2006). According to the U.S. Geological Survey, all cities have low Pb soils (median 16.5 mg/kg) available nearby (Gustavsson et al., 2001). Thus, a proactive primary prevention program to curtail Pb dust and create healthy communities for future generations is possible for all cities.

5. Conclusions

This study extends the knowledge about childhood Pb exposure and latent violence from the scale of the national, U.S. states and counties to the scale of the city, and it supports Patterson's ecological perspective regarding the impact of lead dust on the inhabitability of older urban environments in the U.S. Other things held equal, we find a statistically significant association between tonnages of air Pb released 22 years prior with present period aggravated assault rate; our full statistical model explains 90% of the variation in aggravated assault across US cities examined. The critical toxicology issue is that children are extremely sensitive to Pb dust, and Pb exposure has latent neuroanatomical effects that severely impact future societal behavior and welfare. The risk of exposure persists because past uses of Pb accumulated as dust in urban soils, and thus the accumulated Pb dust remains as a continuing source of exposure. A well-organized policy response is needed to support remedial actions to protect children from legacy Pb dust. By preventing child Pb exposure now, society may realize numerous benefits two decades into the future, including less violence.

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