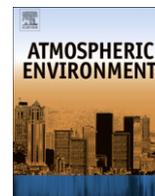


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## Re-suspension of lead contaminated urban soil as a dominant source of atmospheric lead in Birmingham, Chicago, Detroit and Pittsburgh, USA

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### ABSTRACT

Soils in older areas of cities are highly contaminated by lead, due largely to past use of lead additives in gasoline, the use of lead in exterior paints, and industrial lead sources. Soils are not passive repositories and periodic re-suspension of fine lead contaminated soil dust particulates (or aerosols) may create seasonal variations of lead exposure for urban dwellers. Atmospheric soil and lead aerosol data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) database were obtained for Pittsburgh (Pennsylvania), Detroit (Michigan), Chicago (Illinois), and Birmingham (Alabama), USA. In this study the temporal variations of atmospheric soil and lead aerosols in these four US cities were examined to determine whether re-suspended lead contaminated urban soil was the dominant source of atmospheric lead. Soil and lead-in-air concentrations were examined to ascertain whether lead aerosols follow seasonal patterns with highest concentrations during the summer and/or autumn. In addition, atmospheric soil and lead aerosol concentrations on weekends and Federal Government holidays were compared to weekdays to evaluate the possibility that automotive turbulence results in re-suspension of lead contaminated urban soil. The results show that the natural logs of atmospheric soil and lead aerosols were associated in Pittsburgh from April 2004 to July 2005 ( $R^2 = 0.31$ ,  $p < 0.01$ ), Detroit from November 2003 to July 2005 ( $R^2 = 0.49$ ,  $p < 0.01$ ), Chicago from November 2003 to August 2005 ( $R^2 = 0.32$ ,  $p < 0.01$ ), and Birmingham from May 2004 to December 2006 ( $R^2 = 0.47$ ,  $p < 0.01$ ). Atmospheric soil and lead aerosols followed seasonal patterns with highest concentrations during the summer and/or autumn. Atmospheric soil and lead aerosols are 3.15 and 3.12 times higher, respectively, during weekdays than weekends and Federal Government holidays, suggesting that automotive traffic turbulence plays a significant role in re-suspension of contaminated roadside soils and dusts. In order to decrease urban lead aerosol concentrations, lead deposition and subsequent children's seasonal exposure, lead contaminated urban soils need remediation or isolation because the legacy of lead continues to pose unnecessary and preventable health risks to urban dwellers.

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## 1. Introduction

### 1.1. Lead dust contaminated urban soils

During the 20th century massive quantities of lead (Pb) were used in commercial and industrial products which contaminated soil. In the 1970s, the presumed dominant source of soil Pb contamination was Pb-based house paint (Ter Haar and Aronow, 1974). A subsequent study of garden soils conducted in metropolitan Baltimore, Maryland, raised questions about that assumption; soil around Baltimore's inner city buildings, predominantly unpainted brick, exhibited the highest amounts of Pb, while the

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soils outside of the inner city, where buildings were commonly constructed with wood siding coated with Pb-based paint, contained comparatively low amounts of Pb (Mielke et al., 1983). These findings suggested that Pb-based house paint could not fully account for the observed patterns of urban soil Pb and that a different source and process of contamination needed to be considered.

The mass of Pb additives used in gasoline in the US has been documented in detail by Mielke et al. (2010). In the US, motor vehicles used gasoline containing tetraethyl Pb additives from the 1920s to 1995. By the 1950s, Pb additives were contained in virtually all grades of gasoline. By 1986, when leaded gasoline underwent a rapid phase-down but not yet completely withdrawn, 5–6 million metric tons of Pb had been used as a gasoline additive across the US, of which, about 75% was released into the atmosphere (Chaney and Mielke, 1986; Mielke and Reagan, 1998). Thus, an estimated 4–5 million tons of Pb has been deposited into the US environment by way of gasoline-fueled motor vehicles (Mielke, 1994; Mielke et al., 2011). Finally, the accumulation of soil Pb from leaded gasoline emissions has been shown to be proportional to highway traffic volume (Mielke et al., 1997).

### 1.2. Soil re-suspension

Urban soil re-suspension has been studied by using the Inter-agency Monitoring of Protected Visual Environments database (IMPROVE, 2011). Laidlaw and Filippelli (2008) demonstrated that soils at eight sites located across America become re-suspended into the atmosphere during summertime and autumn when soils are dry and evapotranspiration maximized. Wells et al. (2007) documented the same phenomena at 15 IMPROVE locations in

the western United States. Similarly, in Bakersfield, California, Young et al. (2002) observed that 74% of PM10 from July through September 1988 was composed of soil.

### 1.3. Re-suspension of urban soil as a source of lead aerosols

Limited data has been published on the seasonal variations in atmospheric Pb in the United States. However, summertime peaks of atmospheric Pb have been observed in Washington D.C. (Green and Morris, 2006; Melaku et al., 2008), Boston (USEPA, 1995), New York (Billick et al., 1979) New Jersey (Edwards et al., 1998; Yiin et al., 2000), and Chicago (Paode et al., 1998). Therefore, in order to explore the hypothesis that airborne urban soil contributes to the burden of Pb aerosols, one of the objectives of this study was to analyze temporal variations in atmospheric soil and Pb aerosols in four US cities: Pittsburgh, Detroit, Chicago, and Birmingham (Fig. 1). The specific goals of the study were to test whether re-suspended urban soil was the dominant source of Pb aerosols in the four cities, and whether atmospheric soil and Pb aerosols follow seasonal patterns and if the highest concentrations occurred during the summer and/or autumn. Additionally, the study examines whether atmospheric soil and Pb aerosol concentrations were lower on the weekends and Federal Government holidays relative to weekdays to evaluate the possibility that automotive turbulence causes re-suspension of Pb contaminated urban soil to produce increases in Pb aerosols into the urban atmosphere. Finally, we discuss the possible link between re-suspension of Pb contaminated urban soil as a contributor to a substantial public health issue, especially for children (Filippelli et al., 2005; Jones et al., 2009; Lanphear et al., 2002).

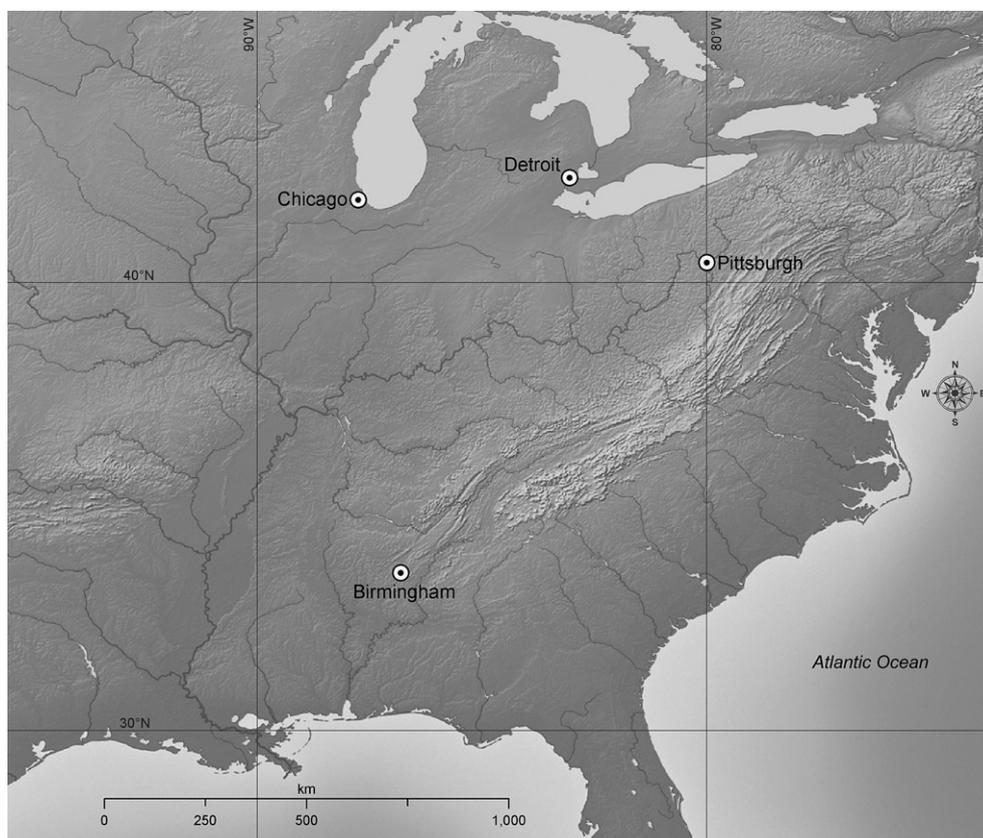


Fig. 1. The locations of Pittsburgh (Pennsylvania), Detroit (Michigan), Chicago (Illinois), and Birmingham (Alabama) in the USA, the cities examined in this study.

**Table 1**  
Descriptive statistics of variables analyzed.

	Pittsburgh		Detroit		Chicago		Birmingham		Overall	
	N	Mean (Std. Dev)	N	Mean (Std. Dev)	N	Mean (Std. Dev)	N	Mean (Std. Dev)	N	Mean (Std. Dev)
Humidity	147	74.51 (13.95)	192	70.34 (12.58)	213	65.23 (13.16)	309	69.14 (12.92)	861	69.35 (13.40)
Sea level pressure (mb)	147	2,071 (13.94)	192	2,072 (15.48)	213	2,071 (14.25)	309	2,073 (10.94)	861	2,072 (13.41)
Temperature (°C)	147	12.39 (9.39)	192	8.56 (10.74)	213	10.38 (10.91)	309	18.46 (7.93)	861	13.22 (10.46)
Visibility (km)	147	13.26 (3.30)	192	14.10 (2.79)	213	14.42 (2.56)	309	14.05 (2.48)	861	14.02 (2.74)
Wind (km h <sup>-1</sup> )	147	11.61 (4.78)	192	12.77 (5.32)	213	15.14 (5.74)	309	9.15 (5.19)	861	11.86 (5.78)
Weekends/holidays	147	0.31 (0.47)	193	0.33 (0.47)	213	0.32 (0.47)	309	0.32 (0.47)	862	0.32 (0.47)
Air soil	146	0.99 (0.66)	193	0.812 (0.54)	213	0.810 (0.51)	309	1.964 (1.806)	861	1.255 (1.287)
Air lead	147	0.013 (0.014)	193	0.005 (0.003)	213	0.006 (0.004)	309	0.223 (0.033)	862	0.013 (0.022)

**Table 2**  
Ordinary least squares and random effects generalized least squares regression models predicting the natural log of air Pb as a function of the natural log of air soil.

	Pittsburgh marginal effect	Detroit marginal effect	Chicago marginal effect	Birmingham marginal effect	Overall marginal effect
Air soil	0.709*** (0.088)	0.848*** (0.063)	0.710*** (0.070)	0.922*** (0.056)	0.841*** (0.034)
Constant	-4.574*** (0.059)	-5.305*** (0.040)	-5.104*** (0.046)	-4.713*** (0.049)	-4.898*** (0.174)
N	146	193	213	309	861
F	64.92	180.84	104.58	269.69	
R <sup>2</sup> overall	0.3108	0.4863	0.3214	0.4677	0.5046
R <sup>2</sup> within					0.4185
R <sup>2</sup> between					0.7548
Wald χ <sup>2</sup>					621.13
N cities					4

Note: Standard errors in parentheses. \*\*\**p* < 0.01, \*\**p* < 0.05, \**p* < 0.1.

## 2. Methods

### 2.1. Data

Mielke et al. (2011) ranked the top 90 cities in the United States by the amount of Pb additives emitted from automobiles during 1950–1982. These included Pittsburgh, Detroit, Chicago, and Birmingham, which were ranked 19th, 4th, 3rd and 42nd, respectively. Atmospheric soil and Pb aerosol data were obtained from the Interagency Monitoring of Protected Visual Environments (IMPROVE) stations in each of the above named cities (IMPROVE, 2011). Atmospheric soil and Pb aerosol data were obtained for the following time periods: Pittsburgh, April 2004–July 2005; Detroit, November 2003–July 2005; Chicago, November 2003–August 2005; and Birmingham, May 2004–December 2006. Air monitoring station data were provided at the daily time interval. The four cities represent a range sizes, climatic regions, and atmospheric Pb aerosol levels.

To derive atmospheric soil estimates, IMPROVE provides a mineral equation of the assumed primary constituents in soil, including Al, Si, Ca, Fe, and Ti (IMPROVE soil estimation calculation, 2003). Soil composition variability is derived by the quadratic sum of constituent concentrations, assuming independence of measurement uncertainties:

$$[d(\text{soil})]^2 = [2.20 \times d(\text{Al})]^2 + [2.49 \times d(\text{Si})]^2 + [1.63 \times d(\text{Ca})]^2 + [2.42 \times d(\text{Fe})]^2 + [1.94 \times d(\text{Ti})]^2$$

In addition to atmospheric soil and Pb aerosol data, we gathered local weather data on variables known to influence seasonality of atmospheric concentrations of soil and Pb, including average relative humidity (%), average sea level pressure (mb), average temperature (°C), average visibility (km), and average wind speed (km h<sup>-1</sup>) (cf. Laidlaw and Filippelli, 2008). Descriptive statistics on atmospheric soil and Pb aerosol conditions as well as weather conditions in Pittsburgh, Detroit, Chicago, and Birmingham are

**Table 3**  
Random effects generalized least squares regression coefficients predicting Air Pb and Air soil.

	Air lead Model 1	Air lead Model 2	Air soil Model 3	Air soil Model 4
	<i>b</i>	beta	<i>b</i>	beta
Humidity	-0.006* (0.003)	-0.073* (0.038)	-0.009*** (0.002)	-0.126*** (0.024)
Sea level pressure	0.008*** (0.177)	0.103*** (0.034)	0.007*** (0.002)	0.100*** (0.022)
Temperature	0.028*** (0.003)	0.288*** (0.033)	0.038*** (0.002)	0.400*** (0.021)
Visibility	-0.049*** (0.014)	-0.135*** (0.037)	-0.031*** (0.009)	-0.084*** (0.024)
Wind speed	-0.068*** (0.005)	-0.393*** (0.033)	-0.034*** (0.004)	-0.198*** (0.021)
Weekend/holiday	-0.122** (0.0600)	-0.122** (0.060)	-0.289*** (0.038)	-0.289*** (0.038)
Constant	-19.327*** (5.358)	-4.910*** (0.034)	-14.45*** (3.44)	0.024 (0.022)
N	861		860	
R <sup>2</sup> within	0.2159		0.4025	
R <sup>2</sup> between	0.8407		0.9867	
R <sup>2</sup> overall	0.3362		0.5034	
Wald χ <sup>2</sup>	432.49		864.65	
N cities	4		4	

Note: Standard errors in parentheses. \*\*\**p* < 0.01, \*\**p* < 0.05, \**p* < 0.1.

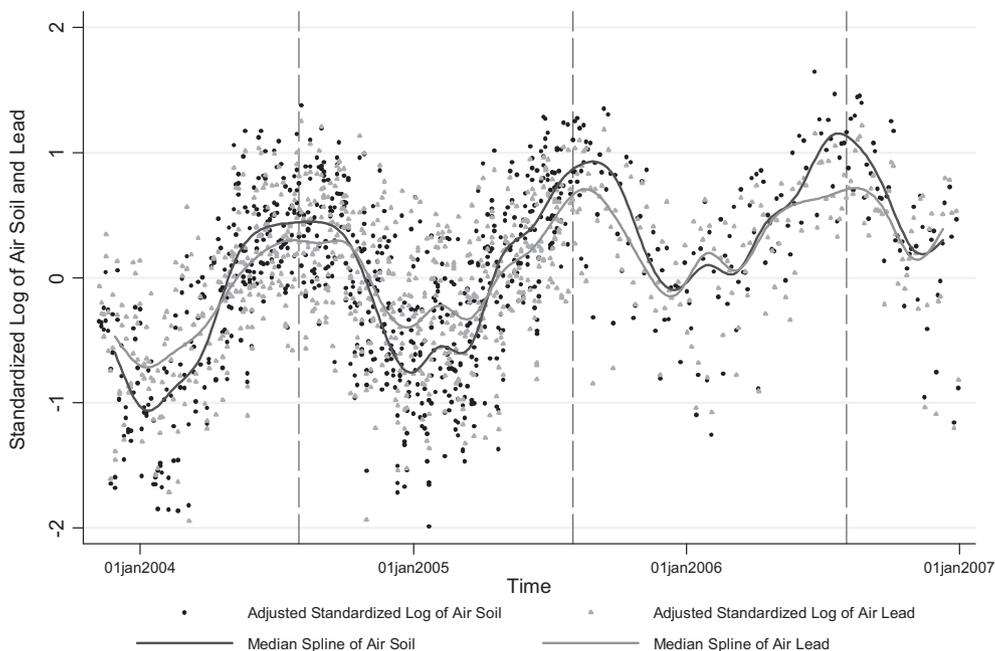


Fig. 2. Weather adjusted air Pb and air soil over time, including median spline fits, for Pittsburgh, Detroit, Chicago and Birmingham.

presented in Table 1. Data show that average atmospheric soil ( $1.96 \mu\text{g m}^{-3}$ ) and Pb ( $0.22 \mu\text{g m}^{-3}$ ) conditions are highest in Birmingham, followed by Pittsburgh ( $0.99 \mu\text{g m}^{-3}$ ,  $0.013 \mu\text{g m}^{-3}$ ), Chicago ( $0.81 \mu\text{g m}^{-3}$ ,  $0.006 \mu\text{g m}^{-3}$ ), and Detroit ( $0.81 \mu\text{g m}^{-3}$ ,  $0.005 \mu\text{g m}^{-3}$ ).

## 2.2. Statistical procedures

To address the correlation between atmospheric Pb and soil, we used a *random effects generalized least squares model*. The *random effects model* allows each city to have its own intercept, yielding

a weighted average of *between* and *within* city effects. Letting  $j$  denote the city,  $i$  denote the day an atmospheric Pb reading is taken, and  $y_{ij}$  denoting the atmospheric Pb level on day  $i$  in city  $j$ . Our regression estimator is modeled as:  $y_{ij} = \beta_0 + \beta_1 S_{ij} + u_j + e_{ij}$ , where,  $\beta_0$  is the average air Pb across cities, and  $S_{ij}$  is the daily observation of atmospheric soil in a given city. The model divides the residual term into two components: (i) a city-specific error component, given by  $u_j$ ; and (ii) a station specific error component, which varies between daily air station reading and city, given by  $e_{ij}$ . The city level residual  $u_j$  is the difference between city  $j$ 's atmospheric Pb mean and the overall mean, with the mean of

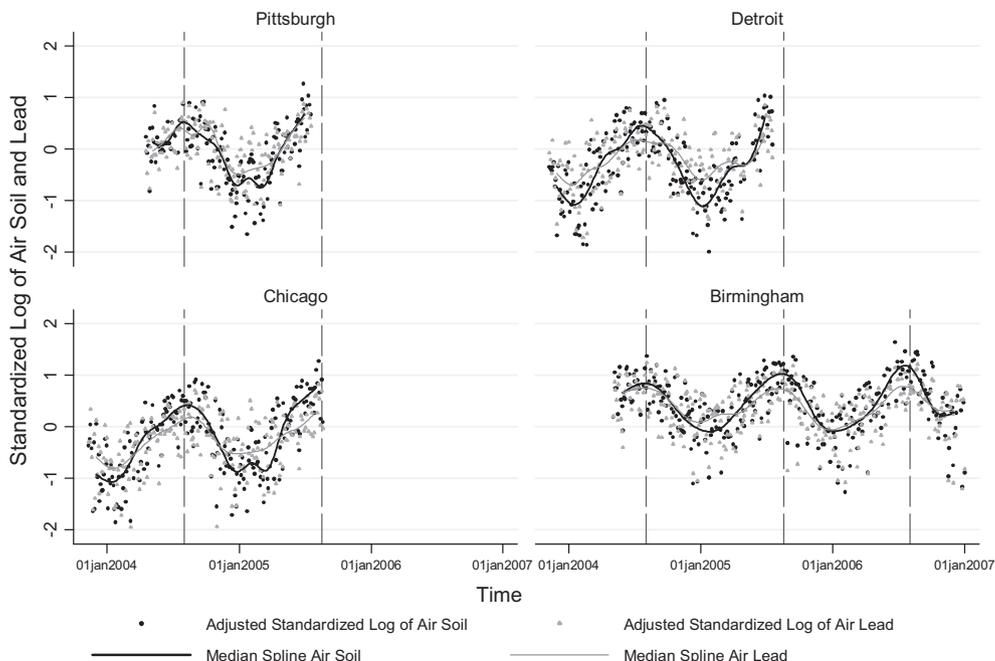


Fig. 3. Weather adjusted air Pb and air soil over time, including median spline fits, for Pittsburgh, Detroit, Chicago and Birmingham.

**Table 4** Ordinary least squares and random effects generalized least squares regression coefficients predicting Air Pb and Soil.

	Pittsburgh		Detroit		Chicago		Birmingham		Overall	
	AL	AS	AL	AS	AL	AS	AL	AS	AL	AS
February	0.072 (0.178)	0.050 (0.179)	0.200 (0.141)	0.252* (0.138)	0.223 (0.151)	0.260* (0.145)	0.098 (0.135)	0.053 (0.134)	0.164* (0.085)	0.178** (0.088)
March	-0.041 (0.173)	-0.064 (0.174)	0.340*** (0.133)	0.477*** (0.131)	0.067 (0.145)	0.303** (0.139)	0.155 (0.133)	0.265** (0.132)	0.146* (0.082)	0.279*** (0.085)
April	0.165 (0.157)	0.653*** (0.158)	0.423*** (0.141)	0.865*** (0.138)	0.326** (0.147)	0.822** (0.141)	0.215 (0.131)	0.409*** (0.130)	0.305*** (0.082)	0.707*** (0.085)
May	0.391*** (0.150)	0.791*** (0.151)	0.612*** (0.149)	1.12*** (0.146)	0.565** (0.149)	1.03*** (0.143)	0.418*** (0.121)	0.634*** (0.120)	0.563*** (0.079)	0.960*** (0.082)
June	0.613*** (0.151)	1.01*** (.152)	0.906*** (0.135)	1.54*** (0.132)	0.762** (0.149)	1.39*** (0.143)	0.751*** (0.122)	0.955*** (0.121)	0.813*** (0.082)	1.27*** (0.081)
July	0.716*** (0.159)	1.17*** (.160)	0.873** (0.146)	1.56*** (0.143)	0.778** (0.147)	1.45*** (0.143)	0.701*** (0.122)	0.996*** (0.121)	1.35*** (0.083)	1.38*** (0.086)
August	0.645*** (0.169)	1.04*** (.170)	0.886*** (0.166)	1.39*** (0.163)	0.942*** (0.151)	1.48*** (0.145)	0.821*** (0.120)	0.939*** (0.082)	1.38*** (0.086)	1.38*** (0.086)
September	0.698*** (0.173)	1.11*** (0.174)	1.01*** (0.180)	1.57*** (0.177)	0.922*** (0.180)	1.51*** (0.174)	0.544*** (.120)	0.803*** (0.119)	0.865*** (0.086)	1.32*** (0.090)
October	0.420** (0.173)	0.574*** (.174)	0.427** (0.166)	0.778*** (0.163)	0.360** (0.180)	0.781*** (0.174)	0.364*** (0.120)	0.490*** (0.119)	0.535*** (0.086)	0.821*** (0.089)
November	0.257 (0.173)	0.505*** (0.174)	0.372*** (0.139)	0.605** (0.136)	0.317** (.153)	0.570*** (0.147)	0.219* (0.120)	0.289** (0.119)	0.357*** (0.081)	0.568*** (0.084)
December	-0.291* (0.173)	-0.200 (0.174)	0.159 (0.135)	0.220* (0.132)	.109 (0.147)	0.168 (0.141)	.042 (0.121)	-0.026 (0.120)	0.092 (0.080)	.114 (0.083)
Constant	-0.330*** (0.119)	-0.675*** (0.120)	-0.686*** (0.093)	-1.12*** (0.091)	-0.722*** (0.102)	-1.03*** (0.099)	-0.044 (0.092)	-0.110 (0.091)	-0.464*** (0.057)	0.747 (0.059)
N	147	147	192	192	213	213	309	309	861	861
R <sup>2</sup> within									0.319	0.542
R <sup>2</sup> between									0.679	0.621
R <sup>2</sup> overall									0.299	0.486
Wald X <sup>2</sup>	0.392	0.588	0.359	0.637	0.331	0.603	0.306	0.459	362.04	802.09

Notes: Standard errors in parentheses. January is the reference month. \*\*\*p < 0.01, \*\* p < 0.05, \* p < 0.1. AL = Air Lead, AS = Air Soil.

atmospheric Pb for city  $j$  being  $\beta_0 + u_j$ . The city-specific error component can be thought of as the combined effects of omitted city characteristics or unobserved heterogeneity (Rabe-Hesketh and Skrondal, 2008). The daily station reading residual  $e_{ij}$  is the difference between observed atmospheric Pb level on given day  $i$  and the average atmospheric Pb of that station's city mean,  $e_{ij} = y_{ij} - (\beta_0 + u_j)$ . Both residual terms are assumed to obey a Gaussian structure with zero means:  $u_j \sim N(0, \sigma_u^2)$  and  $e_{ij} \sim N(0, \sigma_{e_{ij}}^2)$ .

To address the seasonality of atmospheric Pb and soil, and using the same modeling logic above, we regressed both atmospheric Pb and soil on the weather variables of average relative humidity, average sea level pressure, average temperature, average visibility, and average wind speed to derive seasonally-adjusted atmospheric Pb and soil estimates. The weather-adjusted air Pb and soil estimates were then graphed on the daily time interval, fitting the distribution of weather-adjusted daily readings of air Pb and soil with median splines. This analysis was performed for all cities combined, and then for each city independently. The graphical analysis provides a visual check to see if daily variations in weather-adjusted air Pb and soil estimates approximate to several outcomes including: Observed seasonal cycles in the proportion of children screened with blood Pb > 10  $\mu\text{g dL}^{-1}$  (Haley and Talbot, 2004); and age-adjusted average blood Pb (USEPA, 1995; Havlena et al., 2009). Finally, weather-adjusted air Pb and soil estimates were regressed on monthly dummy/binary variables to see if coefficients rise noticeably in the months of June, July, August and September, which are known periods when children presented with elevated blood Pb.

To test whether anthropogenic turbulence may drive re-suspension of Pb-contaminated urban soil into the atmosphere we performed independent sample t-tests to compare atmospheric soil and Pb aerosol concentrations on weekdays and weekends/Federal Government holidays. Both industrial activities and vehicle miles traveled decline significantly on weekends and Federal Government holidays mandating closure of businesses including: New Year's Day, Martin Luther King Day, President's Day, Memorial Day, Independence Day, Labor Day, Columbus Day, Veterans Day, Thanksgiving Day, and Christmas Day.

### 3. Results

#### 3.1. Least squares regression models for each city

Results for ordinary least squares regression models for each city and a random effects generalized least squares regression model combining city observations are suitable for statistical procedures used herein (Table 2). We hypothesized the natural log of air Pb was a function of the natural log of air soil. Marginal effects are reported, indicating the predicted percent change in atmospheric Pb for a percent change in atmospheric soil. Results show that atmospheric Pb and soil are correlated significantly. The expected percent increase in atmospheric Pb for a percent increase of air soil is 0.709 (95% CI, 0.535 to 0.882) in Pittsburgh, 0.848 (95% CI, 0.724 to 0.973) in Detroit, 0.710 (95% CI, 0.573 to 0.847) in Chicago, and 0.922 (95% CI, 0.812 to 1.033) in Birmingham. The soil elasticity or marginal effect of atmospheric Pb is approximately equal across all the cities analyzed, given overlapping intervals of confidence. In the random effects model combining observations from all cities, we find a marginal effect of 0.841 (95% CI, 0.775 to 0.908). Model residuals from the random effects regression have a mean of zero (1.11e-09) and white noise properties of Gaussianity and homoskedasticity. Overall, both within and across the four cities examined, atmospheric Pb and soil co-varied in near proportional terms for the four cities tested.

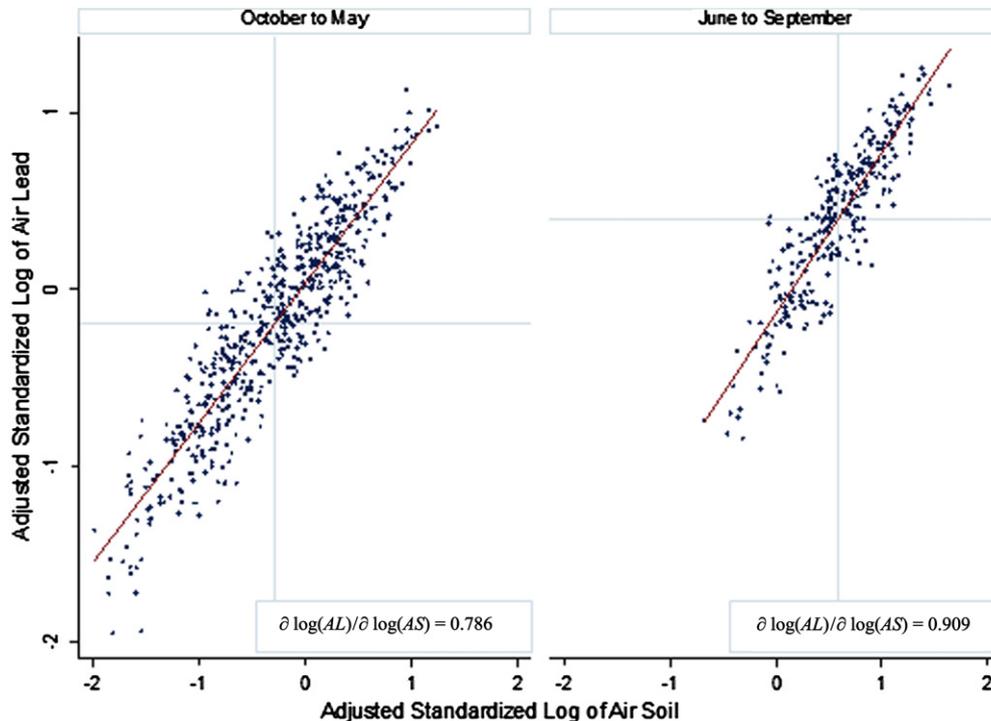


Fig. 4. Weather adjusted air lead versus air soil with linear fit for peak months (June, July, August, and September) and non peak months (October through May) for Pittsburgh, Detroit, Chicago and Birmingham combined.

### 3.2. Atmospheric soil and Pb aerosols as a function of weather variables

The random effects regression models of atmospheric Pb and soil as a function of weather variables were determined (Table 3). Allowing  $j$  to denote city,  $i$  to denote the day of the atmospheric Pb or atmospheric soil station reading, and  $y_{ij}$  denote the atmospheric Pb or soil level on day  $i$  in city  $j$ , our regression estimator is modeled as:  $y_{ij} = \beta_0 + \beta_1 W_{ij} + u_j + e_{ij}$ , where,  $\beta_0$  is the average air Pb or average air soil across cities, and  $W_{ij}$  is a vector of weather variables observed daily and corresponding to a given city. The double component residual of the random effects model obeys the same logic as described above. Both regular ( $b$ ) and standardized coefficients (beta) are reported. In Model 2, we find that standard deviation increases in humidity (beta =  $-0.073$ ), visibility (beta =  $-0.135$ ), and wind speed (beta =  $-0.393$ ), significantly decrease atmospheric Pb, whereas sea level pressure (beta =  $.103$ ) and temperature (beta =  $0.288$ ) function to increase atmospheric Pb. To be more specific, a standard deviation increase in observed temperature increases the expected level of atmospheric Pb by over 1/4th of a standard deviation. Weather variables behave similarly in direction and magnitude in prediction of atmospheric soil. Adjusting for weather variables, both atmospheric Pb and soil appear sensitive to anthropogenic turbulence. Measured as a binary variable of weekday = 0, and weekend/Federal Government holiday = 1, we find that air Pb (beta =  $-0.122$ ) and air soil (beta =  $-0.289$ ) levels are decreased significantly during days of rest and leisure.

Across and within the cities examined, atmospheric soil and Pb appear to have cyclical properties of consistent periodicity, angle function and amplitude, peaking in the summer/autumn months June, July, August and September, and contracting noticeably in the winter months of October through May (Table 3; Figs. 2 and 3). The behavior of both Pb aerosols and air soil splines appear to match closely the cyclical behavior of blood Pb outcomes in children observed across many cities and time periods (Laidlaw et al., 2005).

### 3.3. Models of weather-adjusted Pb aerosols and air soil values

Regression models of weather-adjusted air Pb and air soil values as a function of monthly dummy variables were also developed (Table 4), revealing that within and across the study cities, air Pb and soil follow a seasonal pattern, which is distinguishable from a chance occurrence. Reported coefficients represent expected increases or decreases in average atmospheric Pb and soil in specified months as compared to our reference months of October through May. Coefficients are expressed in standard deviation terms. For example, in the random effects model, incorporating observations from all cities, we find that in the months of June, July, August, and September, atmospheric soil levels are between 1.27 and 1.38 standard deviations higher than in the months of October through May. Lead aerosol levels are similarly higher in the months June, July, August and September, rising above the October through May levels by 0.813 to 0.939 standard deviations. Again, these summer and autumn months correspond to the same months where the incidence of child Pb poisoning is highest (Laidlaw et al., 2005).

The theoretical expectation is that the relationship between air Pb and air soil ought to strengthen in the peak months of June through September as compared to non-peak months of October through May. Not only do mean values noticeably increase on both dimensions, but the elasticity of the relationship between air Pb and air soil statistically increases ( $\partial \log(AL)/\partial \log(AS) = 0.786$  versus 0.909; Fig. 4). The same pattern is evident in each of the individual cities (Fig. 5). This result of a rising marginal effect in the summer/autumn months of June, July, August, and September is consistent with the soil re-suspension mechanism of atmospheric Pb aerosols.

### 3.4. Atmospheric soil and Pb aerosol levels on weekdays and weekends/Federal Government holidays

Independent sample  $t$ -test results comparing average atmospheric soil and Pb aerosol levels on weekdays and weekends/

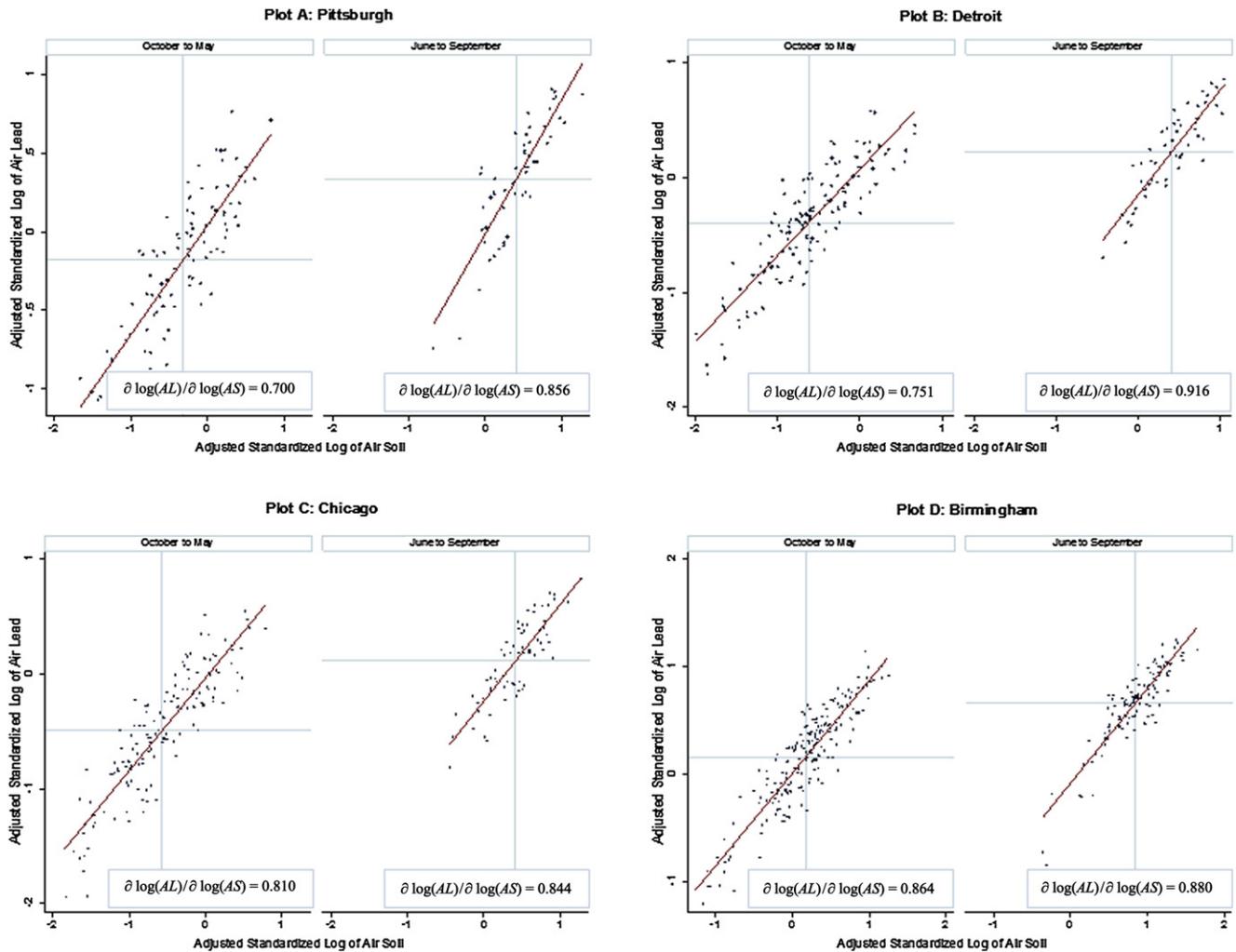


Fig. 5. Weather adjusted air lead versus air soil with linear fit for soil during air peak months (June, July, August, and September) and non-peak months (October through May) by city, Pittsburgh, Detroit, Chicago and Birmingham.

Federal Government holidays provide an interesting insight into the role of atmospheric turbulence in soil re-suspension (Table 5). The main purpose here is to test whether anthropogenic traffic turbulence influences observed levels of soil and Pb in the atmosphere. By exploiting the weekly and holiday structure of labor and leisure routines in the US, we were able to conduct a natural experiment examining the role of anthropogenic turbulence of soil and atmospheric Pb. Results show that both weather adjusted Pb aerosols ( $t = 4.191$ ,  $\Pr(W_d > W_e) = 0.01$ ) and air soil levels ( $t = 6.443$ ,  $\Pr(W_d > W_e) = 0.01$ ) are significantly lower on weekends/holidays across all cities examined. Moreover, Pb aerosol levels are 3.12 times higher during weekdays than weekends, and air soil levels are 3.15 times higher during weekdays than weekends. These findings are consistent with the concept that anthropogenic turbulence influences both atmospheric soil and Pb aerosol

concentrations, which in turn may drive exposure inside residential homes.

#### 4. Discussion

##### 4.1. Study limitations

Atmospheric soil and Pb aerosol concentrations were only observed at one location in each of the cities, and it is not known if these temporal patterns would be confirmed spatially throughout each of the cities. Also, causality between atmospheric soil re-suspension and Pb aerosol concentrations was inferred and could not be proved from this study; although we note that the association is strongly correlated and consistent between the cities examined. The potential health impacts of soil Pb re-suspension as

Table 5

Descriptive statistics and independent samples  $t$ -test results comparing weekdays and weekends/Federal Government holidays.

	Adjusted standardized log of air lead				Adjusted standardized log of air soil			
	Weekday ( $W_d$ ) Mean (Std. Error)	Weekend ( $W_e$ ) Mean (Std. Error)	Difference	$t$ -test	Weekday ( $W_d$ ) Mean (Std. Error)	Weekend ( $W_e$ ) Mean (Std. Error)	Difference	$t$ -test
Overall	0.0569 (0.0240)	-0.1209 (0.0349)	0.1778 (0.0424)	4.191***	0.1037 (0.0288)	-0.2232 (0.0416)	0.3268 (0.0507)	6.443***

Note: \*\*\* $\Pr(W_d > W_e) = 0.01$ .

indicated by other studies can also only be inferred because childhood blood Pb data was not available for the four cities examined.

#### 4.2. Re-suspension of Pb contaminated soil and vehicle traffic

By definition, atmospheric soil particles have been re-suspended from the ground surface. As observed in multiple locations in the US, atmospheric soil peaks in the summer and autumn during periods of high evapotranspiration potential and low soil moisture (e.g. Laidlaw and Filippelli, 2008; Wells et al., 2007). Given that, as reviewed by Mielke et al. (2011), many urban soils have been contaminated with Pb, it is logical to conclude that when these soils are re-suspended at higher rates during the summertime, atmospheric Pb aerosols will also increase. The contention that Pb contaminated soil is a major source of urban atmospheric Pb, as indicated by the results of this study, is supported by the published literature.

Soil Pb particles are thought to be re-suspended into the atmosphere during the summertime and autumn where they penetrate into the interior of homes and settle on contact surfaces (Layton and Beamer, 2009). Cho et al. (2011) conducted a literature review of the concentrations and size distributions of ambient airborne Pb containing particulate matter, and revealed that during the era of leaded gasoline airborne particle-bound Pb was typically submicron sized whereas after the withdrawal of leaded gasoline, the largest mode of the size distribution of particles shifted to particles  $> 2.5 \mu\text{m}$  (typically associated with larger particles such as soil dust). Since the phase-out of leaded gasoline, airborne Pb concentrations have significantly decreased in urban areas. Cho et al. (2011) concluded that “near-roadway dust” or near industrial sources (when applicable) have become the two most important contemporary sources of Pb in the atmosphere. In Baltimore, Maryland, soil re-suspension has also been observed to be higher in the high traffic older urban areas than in the newer low traffic suburban areas (Simons et al., 2007).

International studies also support our findings. In Sydney Australia, Davis and Birch (2011) measured bulk atmospheric Pb deposition near two background sites located at least 500 m from a major roadway and adjacent to three roadways with traffic volumes of 2000, 47,500 and 84,500 vehicles per/day. This study showed that the Pb flux at these sites was 12, 29, 38, 83 and  $106 \mu\text{g m}^{-2} \text{day}^{-1}$ , respectively, and was also proportional to traffic volume, corroborating Cho et al.’s (2011) review, which also showed that re-suspension of Pb contaminated roadside soils resulted from truck and automobile turbulence on high traffic roadways. In Berlin, Germany, Lenschow et al. (2001) observed that at curb-sides on main streets, the PM10 concentration is up to 40% higher than the urban background; half of the additional pollution is due to motor vehicle exhaust emission and tire abrasion and the other half due to re-suspended soil particles.

Given that aerosols have a high surface area to mass ratio, they are likely to have a relatively high bio-reactivity. Given their small particle size, they also can invade homes and become deposited on horizontal surfaces more easily than coarse particles (Layton and Beamer, 2009). Consequently, seasonal re-suspension of fine particulates from Pb contaminated urban soils may be driving chronically elevated Pb levels in urban children (Harris and Davidson, 2005; Laidlaw and Filippelli, 2008; Laidlaw et al., 2005; Zahran et al., 2011).

Lead contaminated urban soil is implicated as the major source for atmospheric Pb aerosol loadings. A consequence of the re-suspension of Pb contaminated soil is that it has significant repercussions for ongoing adverse Pb exposures in urban dwelling US children. Pingitore et al. (2009) observed that if Pb contaminated

urban soil is the principal source for airborne Pb in urban settings, then “contaminated soil may set a practical lower limit for future decreases in regulation of airborne lead levels” (Pingitore et al., 2009, p. 5). The Centers for Disease Control and Prevention (CDC) acknowledges that along with Pb-based paint and Pb dust, soil is a major Pb source; the agency does not provide a single recommendation about soil Pb in their guidelines (CDC, 2007).

## 5. Conclusions

In order to decrease urban atmospheric Pb concentrations, subsequent Pb-rich dust deposition and penetration into homes, and its consequent deleterious effect in childhood Pb levels, it is necessary to remediate and or isolate urban soils contaminated with Pb. While the US Federal Government has enacted legislation covering clean air (USEPA, 2010) and clean water (USEPA Federal Water Pollution Control Amendments of 1972), there is no universal clean soil act, although there are several standards pertaining to acceptable values. These guidelines are inconsistent across the US and in light of the evidence, they need to be harmonized and re-evaluated so as to develop a unified strategy to mitigate an unnecessary and preventable exposure pathway.

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