Assessing soil lead contamination at multiple scales in Oakland, California: Implications for urban agriculture and environmental justice

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ABSTRACT

As urban agriculture grows in popularity throughout North America, vacant lots, underutilized parks, and other open spaces are becoming prime targets for food production. In many post-industrial landscapes and in neighborhoods with a high density of old housing stock, the risk of lead (Pb) contamination at such sites is raising concerns. This paper evaluates the extent to which soil Pb contamination may be an obstacle to the expansion of urban agriculture in Oakland, California. Using a combination of soil sampling at 112 sites, GIS, "hot spot" analysis, and reconstructed land use histories, the research reveals that soil Pb concentrations are generally lower than federal screening levels of 400 ppm, but significantly higher in West Oakland, the city's oldest area and home to a predominantly low-income and African American population. Lead levels are significantly lower in the affluent, predominantly white Oakland hills. Spatial analysis at city- and neighborhood-scales reveals clusters of Pb contamination related to land use history. Site-scale analyses at 12 sites reveals a high level of variability (in some cases related to land use history) that must be taken into consideration when planning for urban agriculture.

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Introduction[1]

As urban agriculture grows in popularity, vacant parcels in post-industrial cities have become a prime target for cultivation. Many efforts to transform vacant land into verdant and productive agricultural spaces are spearheaded by individuals and organizations eager to provide healthy and nutritious fresh produce to residents of so-called "food deserts", low-income areas where fresh produce and healthy food options are limited or non-existent due low purchasing power and the market logic of supermarket location (Alkon and Agyeman 2011; Gottlieb & Joshi, 2010). However, as food production begins to ramp up on such land, public concern is growing over potential environmental hazards. Many vacant lots contain contaminants that may be a material legacy of a site's industrial past, or simply a function of its proximity to a freeway or some other source of airborne pollution (Goldenberg, 2009; Murphy, 2009;

Runk, 2011; Seltenrich, 2011). In a cruel twist of irony, much of this vacant land is located within or nearby the very food deserts that food justice-oriented urban agriculturalists intend to serve. Indeed, the same socio-spatial processes responsible for deindustrialization and economic disinvestment can explain the decline in availability of healthy food (Eisenhauer, 2001; McClintock, 2011a).

Many urban soils exhibit high concentrations of both synthetic organic contaminants, such as polychlorinated biphenyls (PCBs) and other dioxins, polycyclic aromatic hydrocarbons, and volatile organic compounds (Aichner, Glaser, & Zech, 2007; Krauss & Wilcke, 2003) and heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn) (Alloway, 2004; Sanchez-Camazano, Sanchez-Martin, & Lorenzo, 1994). Their presence, which originates from both point and non-point sources, has elicited concerns among researchers that produce grown in urban gardens may place the health of consumers at risk (Nabulo, Oryem-Origa, & Diamond, 2006; Scheyer, 2004).

Lead tends to headline discussions over the potential risks of urban agriculture, both because it is ubiquitous in urban areas and because of the health risks it poses. Ingestion of soil and dust are primary pathways of exposure to Pb and a large body of research has shown direct correlations between soil Pb and blood Pb levels. Children are particularly susceptible to Pb poisoning; while adults generally absorb less than 5% of ingested Pb, children absorb up to 50% (Laidlaw & Fillippelli, 2008; Mielke et al., 1983, 2007; Mielke & Reagan, 1998).

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[1] Abbreviations used in this article: CEC = cation exchange capacity; CHHSL = California Human Health Screening Level; EBMUD = East Bay Municipal Utilities District; EPA = United States Environmental Protection Agency; NAIP = National Agriculture Imagery Program; OM = organic matter; OPR = Oakland Parks and Recreation Department.

Lead in urban soils comes from several sources. In industrial areas, Pb is generally attributed to atmospheric deposition downwind from smelting (Douay, Helene, Fourrier, Heyman, & Chateau, 2007; Rawlins, Lark, Webster, & O'Donnell, 2006; Schulin, Curchod, Mondeshka, Daskalova, & Keller, 2007). Along highways, Pb contamination is attributed to exhaust emissions (Gratani, Taglioni, & Crescente, 1992; Teichman, Coltrin, Prouty, & Bir, 1993). In residential areas, most Pb contamination is attributed to paint used for housing (Clark, Brabander, & Erdil, 2006; Sutton et al., 1995; Wu, Edwards, He, Liu, & Kleinman, 2010). Over 6 million Mg of Pb was used in paint in the US between the 1880s and the late 1970s, peaking at 1.2 million Mg used in the 1920s. Even though Pb concentrations in paint declined steeply by mid-century, high levels of Pb remain on the interior and exterior walls houses to this day (Mielke, Gonzales, Powell, & Mielke, 2008; Mielke & Reagan, 1998). A US Department of Housing and Urban Development study estimated that in the US, lead paint covers 1.046 million mi^2 (2.079 million km^2)—roughly a third of the total area of the US—of exterior surfaces of housing stock in the United States, or an average of 996 ft^2 (92.53 m^2) of lead-based paint per housing unit (Jacobs et al., 2002). Much of the exterior paint Pb has ended up in the soil over the past century (Mielke, Blake, Burroughs, & Hassinger, 1984; Sutton et al., 1995); one study reports that 52% of houses built in the US before 1978 have yard soil Pb levels >400 mg kg^{-1}, the US Environmental Protection Agency (EPA) screening level for soil Pb contamination (Jacobs et al., 2002).

Systematic studies of soil contamination on vacant land are vital in order to protect the public from potential risks associated with the expansion of the very urban agriculture programs established to increase access to healthy food. Such an approach represents the application of the "precautionary principle" (Morello-Frosch, Pastor, & Sadd, 2002), in that possible contamination risk should be assessed before urban agriculture projects are started in order to ensure that urban soil is safe for food production. This paper details the assessment of existing and potential urban garden sites in Oakland, California, identifying potential contamination at selected sites, while contributing to a broader understanding of how particular land uses impact soil Pb levels. More specifically, the research attempts to: 1) quantify average soil Pb concentrations across Oakland; 2) characterize variation in soil Pb across land uses and geographic regions at the city-scale; and 3) assess variation in soil Pb levels at the city-, neighborhood-, and site-scales. Finally, it bridges applied geographic environmental justice scholarship on exposure to contaminants and other hazards in urban areas (Maantay & Maroko, 2009; Maroko, 2012) to a rapidly growing body of scholarship devoted to mapping food environments (Gatrell, Reid, & Ross, 2011), both in terms of access (Eckert & Shetty, 2011; Hallett & McDermott, 2011) as well as the impact of existing and potential sites of production (Corrigan, 2011; Kremer & DeLiberty, 2011; Metcalf & Widener, 2011).

Methods

Study area description

This study was conducted in Oakland, California (UTM 10N 37.804444, -122.270833). Three primary topographic zones define the city's physical geography: flatlands, foothills, and hills. The flatlands are low-lying areas adjacent to the San Francisco Bay to the city's west and Alameda Estuary and San Leandro Bay to the south. A large percentage of this land is comprised of fill (e.g., dredged sediment, construction debris, quarried rocks), particularly around the Port of Oakland and the Oakland airport (Welch, 1981). The foothills are formed on a gentle fan of alluvium spreading downwards from the Oakland hills, a series of undulating, parallel ridges

running along the city's eastern portion along a northwest–southeast axis. Part of the state's Coast Range, the Oakland hills have been thrust upwards along the Hayward and Moraga faults over the past million years (Sloan, 2006). Soils are a mix of urban land (highly mixed, heterogeneous fill) and urban land complexes. Endogenous soil series in the flatlands are derived from sedimentary, alluvial parent material, while the hills are dominated by a number of excessively drained loams weathered from uplifted conglomerate and ultrabasic metamorphic rock (Welch, 1981). The region's climate is Mediterranean with wet winters and dry summers with morning fog. September is the hottest month with an average high temperature of 27 °C (80.6 °F), while January is the coldest month with an average high of 14.5 °C (58.1 °F). Average annual precipitation is 582.7 mm (22.9″), with the majority (89%) of the total rainfall occurring between November and April (NOAA, 2004). Native vegetation consists of a mosaic of plant communities, including oak woodland, coastal shrub, and coastal terrace prairie, with large coniferous (redwood) stands in the drainages (Beidleman & Kozloff, 2003).

One of three major cities in the San Francisco Bay Area, Oakland has a population of 391,000. The city's bifurcated physical geography of flatlands and hills, which is roughly delimited by two freeways, also marks socioeconomic differences. Census data reveal a disproportionate concentration of poverty in the flatlands of North, West, and East Oakland, affecting a population that is majority African American, Southeast Asian, and Latino. Most of Oakland's white population lives in the more affluent foothills and hills neighborhoods (U.S. Census Bureau, 2010). The highly spatialized nature of the socioeconomic landscape is due in large part to a history of insurance redlining and racial covenants in the first half of the 20th century and to freeway construction and deindustrialization during the 1960s and 1970s, which demarcated not only areas where particular ethnic groups were allowed to live, but also where investment capital flowed (McClintock, 2011a; Self, 2003; Walker, 2001).

This bifurcation of the socioeconomic landscape into hills and flatlands has defined access to healthy and affordable food in Oakland (Beyers et al., 2008; OFPC, 2010). Areas with limited access to healthy food—so-called "food deserts"—are located in the flatlands and are closely tied to the history of disinvestment (HOPE Collaborative, 2009; McClintock, 2011a; Treuhaft, Hamm, & Litjens, 2009). Over the last decade, several food justice organizations have attempted to address inequitable food access through a variety of programs and policy initiatives. Urban agriculture has figured largely into these efforts and has begun to figure prominently in food systems, public health, and land use planning discussions in Oakland (McClintock, Wooten, & Brown, 2012).

Context of the project

This project emerged in conjunction with research conducted by the author in collaboration with the HOPE Collaborative, a W.K. Kellogg Foundation-funded umbrella organization that convenes public agencies, non-profit organizations, and community members to address inequities in Oakland's food system and built environment (Herrera, Khanna, & Davis, 2009; HOPE Collaborative, 2009). Working with a community advisory committee comprised of HOPE Collaborative members, the author and a research assistant conducted an inventory of vacant land with agricultural potential (McClintock & Cooper, 2009). During the inventory, advisory committee members, many of whom represented urban agriculture and food justice organizations, expressed concern that vacant land in the flatlands might be contaminated and that food production on these lots might expose consumers to health risks. Despite well-intentioned efforts to expand food production on vacant land, no
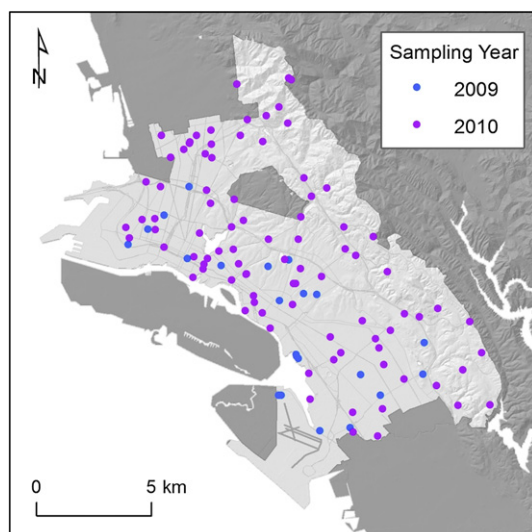
Fig. 1. Soil sampling locations, Oakland, California.

systematic assessment had yet been conducted due to the labor required for sampling and the costs associated with soil analysis. To address this concern, the author applied for and received pilot funding from the University of California Division of Agriculture and Natural Resources Analytical Lab to assess a selection of sites identified by the inventory. The project was scaled up considerably in 2010 following receipt of additional funding from the National Science Foundation. The intent of this second phase was to identify larger-scale spatial trends in soil Pb contamination, while getting baseline soil Pb data for a much larger pool of existing and potential urban garden sites.

Sampling site selection

In 2009, the community advisory committee selected 20 of 495 potential urban agriculture sites identified in the vacant land inventory. The group based their selection on size, proximity to underserved populations, accessibility to public transport, and equal distribution across the Oakland flatlands. In 2010, an additional 140 sites were selected from the inventory in order to map the spatial distribution of Pb levels at the city-scale. Efforts were made to select sites from all regions of the city. Twenty sites were randomly selected from each of Oakland's seven City Council Districts using ArcGIS. Following site visits, however, many of these sites were excluded due to inaccessibility (fences, vegetation, or

steep slopes). Several new sites were later selected from the inventory to fill in geographic gaps. For the most part, sites were evenly distributed across five geographic zones in the flatlands (North, West, Central, and East Oakland) and the Oakland hills (see Fig. 1). A Moran's *I* test of spatial autocorrelation verified that sites were randomly spaced across the city rather than clustered. Upon sampling, each site was classified within a typology of four land use types: garden; park; vacant; or open space (see Table 1). Each land use type served as a proxy for different edaphic types related to the level of anthropogenic disturbance and vegetation typically encountered in a site under such land use. Fig. 2 provides a visual example of each of these land use types.

Plant sampling

To qualitatively characterize the vegetation the four land use types listed in Table 1, representative samples were collected from two vacant sites and two open space sites and identified using a botanical key (Beidleman & Kozloff, 2003). Turf grass species were identified using the online Statewide Integrated Pest Management Program website (UCDANR, 2012).

Soil sampling and analysis

Site-scale sampling

In July 2009, ten of the twenty sites identified by the community advisory committee were selected for a finer-grain analysis in order to assess the extent to which Pb levels vary at the site-scale. An additional site in West Oakland (9th Street) was included in May 2010 on the request of a community development organization interested in developing an urban garden on the site. At the six smallest sites, we overlaid a 25′ × 25′ (7.52 m × 7.52 m) sampling grid in order to detect the spatial distribution of Pb across the site. At three of the larger sites (King's Estates, Oakport, and Harbor Bay) the grid squares were 50′ × 50′ (15.24 m × 15.24 m). At one of the largest sites (Doolittle), grid squares were 100′ × 100′ (30.48 m × 30.48 m), as the site was topographically and edaphically homogenous. At sites where distinctly different soils were visible, each soil was assessed separately (and treated as a separate site); at one site (Oakport), three distinct soils were clearly evident; another (Harbor Bay), two soils were present.

Each grid square was evenly delineated into 9 sub-sections. After surface litter or vegetation was removed, a representative sample was collected from each at a depth of 5–10 cm (depending on penetrability) using a stainless-steel core auger. Geospatial coordinates at each sample point were recorded using a Trimble Pathfinder GPS unit (Trimble Navigation, Ltd., Sunnyvale, CA). The

Table 1
Typology of land use types, level of anthropogenic disturbance, and related edaphic characteristics.

Land use	Level of anthropogenic disturbance	Vegetation	Soils
Garden	++++	Vegetable crops, e.g., chard/beets (*Beta vulgaris*), peas (*Pisum sativum*), collards/kale (*Brassica oleracea*), tomatoes (*Solanum lycopersicum*), lettuce (*Lactuca sativa*)	Frequent, tillage, addition of compost, cultivation
Park	+++	Turf grasses, e.g., Bermuda grass (*Cynodon* spp.), Kentucky bluegrass (*Poa pratensis*), perennial ryegrass (*Lolium perenne*), fescue (*Festuca* spp.); frequently irrigated and mowed, occasionally fertilized	Shallow and compact, high in clay content; often laid on top of clay cap or landscape fabric; heavy foot traffic and occasional vehicle traffic (mowers, trucks)
Vacant	++	Early succession invasive species common in highly disturbed and compacted areas, e.g., yellow star thistle (*Centaurea solstitialis*), fennel (*Foeniculum vulgare*), wild radish (*Raphanus sativus*), curly dock (*Rumex crispus*), slim oat (*Avena barbata*); some sites mowed annually	Compacted, coarse and gravelly soil associated with previous disturbance; occasional traffic, grading, addition of fill, and/or other surface disturbance
Open space	+	Native and exotic grasses and weeds, older succession than vacant; some sites annually mowed or grazed with goats, but natural cycling of litter generally occurs	Deeper, more porous soils, some native; higher in organic matter (OM) due to litter cycling

nine cores from each grid square were mixed together into a single composite sample (henceforth "grid-sample") representing an average of the grid square. A 10 g sub-sample was also taken from each grid-sample and composited to form a "site-sample" representing mean values for the entire site.

City-scale sampling

For the city-scale sites (10 collected in 2009, 92 collected in 2010), 12 soil cores were collected from a depth of 5–10 cm at points evenly distributed within each site. Because the potentially arable area of each site varied in size, samples were collected in a radius ranging from 25′ to 100′. GPS coordinates were logged for each soil core removed. In addition to these 102 samples, site-sample data (described in Site-scale sampling) from each of the 11 site-scale assessments were included in the city-scale dataset, resulting in a total of 113 data points.

Soil analysis

All soil samples were oven dried at 70 °C, ground and sieved using a Standard Model No. 3 Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA) with 2 mm mesh. Total Pb for all samples was determined at the University of California Davis Analytical Lab (Davis, CA) using a nitric acid/hydrogen peroxide closed vessel microwave digestion (Sah & Miller, 1992) and Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). All 2009 site-samples were also analyzed at the UC Davis Lab for bulk density, cation exchange capacity (CEC), organic matter (OM), total nitrogen (N) and carbon (C), exchangeable macro- and micronutrients, and certain metals.

Neighborhood-scale data

To assess Pb distribution at the neighborhood-scale, and to assess if Pb concentration clusters were visible at a more fine-grained level of analysis, we compared our data to sample data collected by the City Slicker Farms Backyard Garden Program. The organization installs raised garden beds for residents throughout West Oakland and routinely collects soil samples prior to installation. Each data point consists of four composited samples collected with a stainless-steel garden trowel from a depth of 0–10 cm. Two composite samples are generally collected for each site, but additional samples are often collected from larger sites. Samples are sent to the U Mass Soil Testing Laboratory (Amherst, MA) and tested for a range of soil fertility indicators and heavy metals using the modified Morgan method (Wolf & Beegle, 1995).

Geospatial and statistical analyses

Points and polygons recorded by the GPS unit were imported into ArcGIS 10 (Esri, Redlands, CA). For site-scale data, we calculated the mean center (a spatial average of *XY* coordinates) of the nine cores collected in each grid square and joined the new coordinate to the corresponding grid sample data (a composite of the nine cores). The same process was used to calculate the mean center of the 12 cores collected for each of the city-scale data points.

Site-scale data were overlaid onto National Agriculture Imagery Program (NAIP) orthophotos (NRCS, 2012). ArcGIS 10 was used for all mapping (Datum/Projection: WGS 1984 UTM Zone 10N) and for calculation of spatial statistics. Datasets were tested for spatial autocorrelation (the degree to which features tend to be

Fig. 2. Examples of four land use types used as an analytical typology: gardens (top-left); parks (top-right); vacant land (bottom-left); and open space (bottom-right).

geographically clustered or dispersed) using Moran's I test. The test calculates the likelihood that clustering within a dataset appears due to random chance. An index value of 1 equals perfect spatial correlation or clustering, 0 equals a random spatial pattern, and −1 equals perfect dispersion (SAS Institute, 2010).

While the Moran's I test is a global test of spatial autocorrelation, where the variance of an individual point is measured against the entire dataset, a local point pattern spatial autocorrelation test can identify individual clusters or "hot spots" within a dataset. The Getis–Ord G_i* test statistic is calculated by comparing the sum of a point and its nearest neighbors to the sum of all points in a given study area. The statistic, a z-value, indicates where high or low values (i.e., values with high standard deviations from the overall mean) cluster spatially (Getis & Ord, 1992). Such an approach has been widely used in applied geographic research to identify clustering of species populations (Ma, Zuckerberg, Porter, & Zhang, 2012), diseases (Wang, Guo, & McLafferty, 2012), crime incidence (Ceccato & Dolmen, 2011), availability of medical care (Zhang, Wong, So, & Lin, 2012), and food retailers (Leslie, Frankenfeld, & Makara, 2012).

Descriptive statistics, means comparisons, and analyses of variance were completed using JMP 9 software (SAS Institute, Cary, NC). One site with a total Pb level of 2262 mg kg^{-1} was removed as an outlier from analysis, as it was several standard deviations higher than the highest quantile. Reported mean values are followed by the standard error (±S.E.). To determine if the data was normally or lognormally distributed, Pb values (both original and log-transformed) were plotted against quantiles, and fit with a regression line. Additionally, a Shapiro–Wilk W test of the original data revealed that the data was not normally distributed and a Kolmogorov's D test verified that the transformed data was actually lognormal. Four tests of equal variance (O'Brien, Brown-Forsythe, Levene, and Bartlett tests) revealed that variance between groups for geographic zones, land use types, and zoning types was unequal. As a result, standard statistical comparisons of means and analysis of variance (which assume normal distribution of data) could not be conducted. Since the total Pb data was also highly skewed and lognormally distributed, comparison of medians and Steel–Dwass multiple comparisons tests for groups of unequal size (a nonparametric version of the Tukey's q-test) were used (SAS Institute, 2010).

Site-scale land use history

To investigate land use histories for the site-scale analyses, a number of maps and aerial photographs were consulted. First, Sanborn Fire Insurance maps from 1899, 1903, 1925, and 1952 for each site were downloaded from the ProQuest Digital Sanborn Maps Library (ProQuest, 2012). City of Oakland street maps published by the Alameda County Chamber of Commerce in 1902, 1909, 1918, 1923, and 1937, as well as aerial ortho-photographs (1:300 scale) taken in 1981 and 1994 for the City of Oakland's Office and Planning and Building were consulted at the University of California Berkeley Earth Sciences Library Map Collection. Finally, NAIP ortho-photos from 2005 to 2009 were also consulted.

Results and discussion

City-scale

Mean total Pb concentration was 108.7 ± 13.7 mg kg^{-1}, and ranged from 3 to 979 mg kg^{-1}. Median Pb concentration was 63.5 mg kg^{-1} (see Table 2). The distribution of the data was lognormal and highly skewed (skewness = 3.957, kurtosis = 18.717), with most sites having Pb levels under 100 mg kg^{-1} (see Table 2).

The lognormal distribution of Pb is consistent with previous research on Pb and other contaminants (Liu, Xia, Yang, Shen, & Liu, 2010; Wang & Qin, 2007). This trend of lognormality is due to either additive or multiplicative processes; in short, a site that is contaminated tends to become even more contaminated (Blackwood, 1992; Limpert, Stahel, & Abbt, 2001). The Moran's I test of total Pb levels revealed no spatial autocorrelation at the city-scale (index = 0.043, p = 0.648). The Getis–Ord G_i* "hot spot" analysis of the city-scale data, however, revealed significant clustering of elevated Pb concentrations in the southern half of West Oakland, and around San Leandro Bay near the Oakland airport.

Overall, total soil Pb levels were much lower than expected. Citywide mean concentrations were far below the EPA's contamination screening levels of 400 mg kg^{-1} but above the recommended California Human Health Screening Level (CHHSL) of 80 mg kg^{-1}. Total Pb levels exceeded background levels. Metamorphic ultramafic (or ultrabasic) rock from the mantle, such as Coast Range Oliophites found in the Green Valley complex, are common in the Bay Area. These rocks are enriched in metals relative to the average levels in the continental crust (Hornberger, Luoma, van Geen, Fuller, & Anima, 1999). In one study, background Pb levels sampled from Oakland soils derived from Great Valley complex, were 21.5 mg kg^{-1}, as much as twice Pb concentrations levels found in soils formed from other geologic units (City of Oakland, n.d.). Nevertheless, mean soil Pb in our study was approximately five to seven times higher than background levels previously reported for the Oakland hills (City of Oakland, n.d.), California (Goldhaber et al., 2009), and the Western United States (Shacklette & Boerngen, 1984). We can therefore assume that elevated levels are due to deposition from anthropogenic sources. Mean Pb levels in Oakland were similar to those found in other urban gardens and urban areas worldwide (Brown et al., 2008; Finster, Gray, & Binns, 2004; Mielke et al., 1983; Morillo, Romero, Madrid, Villaverde, & Maqueda, 2008; Shi et al., 2008; Witzling, Wander, & Phillips, 2011).

Significant differences in total Pb concentrations were identified between geographic zones and land use types. Fig. 3 shows quartile box-and-whisker plots for comparison of medians across (a) geographic zones, (b) land use types, and (c) zoning classification, as well as the geographic distribution of points belonging to these analytical groups. Median Pb levels in West Oakland were higher than in other parts of the city. Levels were likely higher than in the other geographic zones due to the age of the built environment.

Table 2
Mean soil Pb levels (mg kg^{-1}) by geographic zone and land use type at 112 sites in Oakland.

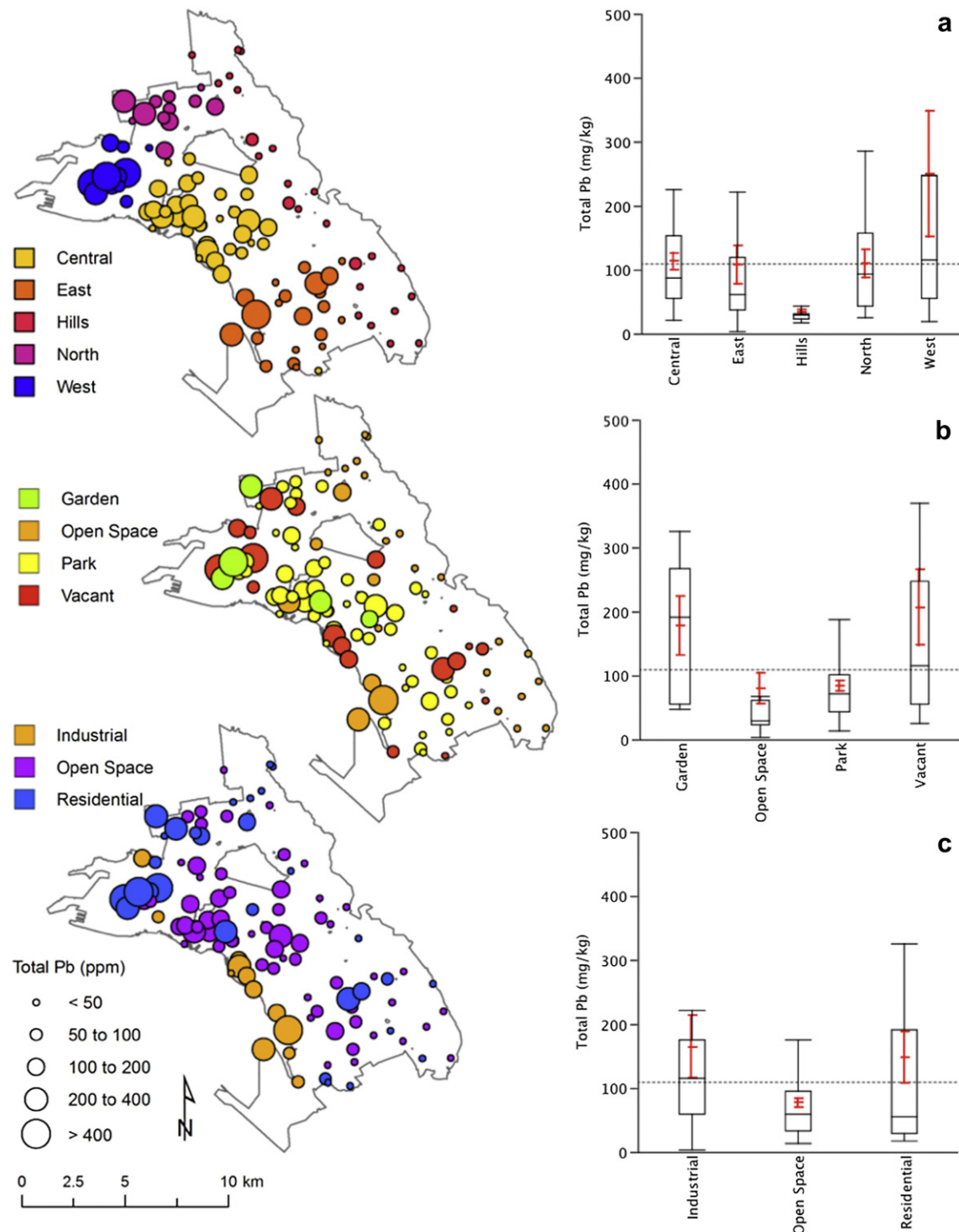| Type	Zone	n	Total Pb (mg kg^{-1})				
			Mean	±S.E.	Median	Min	Max
Garden	Central	3	178	±78.5	148	59	326
	North	2	142	±95.0	142	47	237
	West	1	248	n/a	248	248	248
Open space	Central	6	84	±28.4	60	41	225
	East	6	223	±113.3	176	3	756
	Hills	18	28	±1.7	28	18	45
	North	2	111	±80.0	111	31	191
Park	Central	25	102	±13.5	87	22	315
	East	14	60	±7.3	60	13	107
	Hills	3	54	±11.9	59	31	71
	North	8	76	±14.7	80	25	148
	West	5	93	±30.8	77	20	187
Vacant	Central	5	167	±56.2	154	30	370
	East	4	120	±46.7	95	43	248
	Hills	3	50	±19.3	35	26	88
	North	2	214	±71.3	214	143	286
	West	5	407	±200.6	117	56	979
Total		**112**	**109**	**±13.7**	**64**	**3**	**979**

Fig. 3. Total Pb levels (mg kg^{-1}) by (a) geographic zone, (b) land use type, and (c) zoning classification type of the site and/or surrounding area. Box plots represent 25th, 50th, and 75th percentiles. Red lines indicate the arithmetic mean and one standard error above and below the mean. The dotted line represents the grand mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

West Oakland is the oldest part of the city and the historical nexus of industry, warehousing, and transportation (Bagwell, 1982; Scott, 1959; Walker, 2001).

Furthermore, lead levels here can be attributed to a number of anthropogenic sources. First, smelting and other polluting industries were common in this part of Oakland (Walker, 2001, 2007). Second, West Oakland is ringed by freeways. Vehicle exhaust, particularly from the Port of Oakland, has been correlated with air pollution in West Oakland (Costa et al., 2002; Fisher, Kelly, & Romm, 2006; Palaniappan, Prakash, & Bailey, 2006); Pb contamination originating from vehicle exhaust would have followed these same patterns of deposition. Furthermore, 37% of the housing stock in West Oakland was built before 1940 (U.S. Census Bureau, 2010); indeed, most of the houses in this area date from the 1870s to 1910s (Groth, 2004). As in other studies relating soil Pb to housing (Sutton et al., 1995; Wu et al., 2010), multiple regression analysis of our data

Table 3
Chemical characteristics of soil samples collected from residential yards in West Oakland (n = 260; data source: City Slicker Farms Backyard Garden Program).

	Estimated	Modified Morgan-extracted						pH	CEC (meq cmol$_c^{-1}$)
	Total Pb (mg kg^{-1})	Pb (mg kg^{-1})	Cd (mg kg^{-1})	Ni (mg kg^{-1})	Cr (mg kg^{-1})	P (mg kg^{-1})	Ca (mg kg^{-1})		
Mean	369.8	35.1	0.3	0.4	0.1	58.2	3204.1	6.8	17.8
Median	273.0	20.0	0.2	0.3	0.0	38.0	2526.5	6.9	14.9
Min	0.1	0.0	0.0	0.0	0.0	2.0	690.0	0.5	5.6
Max	3329.0	543.0	3.3	2.3	7.4	2074.0	14620.0	10.1	64.3
Std Err	23.5	3.6	0.0	0.0	0.0	8.6	128.9	0.0	0.7
CV	102.5	163.8	113.8	79.1	653.9	237.4	64.6	10.3	59.8

reveal that the density of pre-1940s housing stock has a significant effect on total Pb levels (McClintock, 2011b).

Mean total soil Pb concentrations in the Oakland hills were significantly lower than in West Oakland (p = 0.0032), North Oakland (p = 0.0039), Central Oakland (p < 0.0001), and East Oakland (p = 0.0038). Low Pb levels in the Oakland hills can be attributed to several factors. First, while the area is primarily residential, the housing stock is much younger. Second, most of the samples collected in the hills were collected in open space. A comparison between land use types reveals that Pb levels in open space were significantly lower than in parks (p = 0.0124), vacant lots (p = 0.0043), and gardens (p = 0.0310). Most of these areas, which are managed by the Oakland Parks and Recreation Department (OPR) or the East Bay Regional Parks District, have never been developed. Not only was construction hindered by steep slopes and residential zoning, but also by the concerted efforts of Bay Area environmentalists during the 1970s to preserve open space (Walker, 2007). Such concentration gradients, from low Pb levels in rural or peri-urban areas to high Pb levels in the urban core, are consistent with other research. In samples taken along three transects across Lubbock, for example, Brown et al. (2008) found that Pb levels were exponentially lower at the outer edge of the city (2.8 mg kg^{-1}) than in the urban core where they peaked at 174 mg kg^{-1}. Mielke et al. found similar patterns in Baltimore (1983) and New Orleans (2007).

Much of the open space (as a land use classification) in East Oakland, however, actually lies in areas zoned for industry along the Alameda Estuary and San Leandro Bay (see Fig. 3b and c). Total Pb levels in East Oakland's open space (223 mg kg^{-1}) were almost ten times higher than in the hills. Median Pb levels in industrial zones were higher than residential and open space zones, and mean total Pb levels slightly higher than in areas zoned as urban open space (p = 0.0879).

Median Pb levels in park soils were slightly higher than under open space land use, but lower than soils in gardens and vacant lots. As a land use classification, parks were defined by a predominance of turf grass. In general, turf grass grown elsewhere is laid down during development of a park. Lead concentrations are therefore only a measure of the total Pb deposited since the site's development. While the age of parks varies considerably, some are obviously recent (as evidenced by new construction and landscaping), which would result in lower Pb levels than in adjacent soils. Lead levels in gardens are likely elevated due to the fact that most are located in residential zones, where Pb contamination from old housing stock is highest. Moreover, all sampled gardens are located in some of the oldest parts of the city: North, West, and Central Oakland.

Neighborhood-scale

Overall, estimated total Pb concentrations at 116 houses in West Oakland were higher than citywide averages, but similar to the West Oakland levels identified in the city-scale analysis (see Table 3 and Fig. 4). Estimated total Pb ranged from 0 to 3329 mg kg^{-1}, with a mean of 370 mg kg^{-1} and a median of 273 mg kg^{-1}. Like the city-scale data, distribution was lognormal (skewness = 4.16, kurtosis = 24.74).

A Moran's I test of spatial autocorrelation for the West Oakland data revealed no significant clustering of total Pb concentrations (index score = 0.062, p = 0.706). A Getis–Ord G_i^* test on the neighborhood-scale data, however, revealed some significant clustering of elevated Pb levels in the southwest corner of West Oakland, mirroring "hot spots" that were also identified in a similar analysis of the city-scale data (see Fig. 5). The clusters identified in both the city-scale and West Oakland datasets is adjacent to a brownfield, the former site of the Phoenix Iron Works, a foundry that operated from 1901 until the early 1990s when the relocation of the Cypress Freeway forced it to shut its doors (Letzing, 2004). Lead is emitted as a byproduct of iron smelting and elevated soil Pb levels are common in areas surrounding iron smelters (Schulin et al., 2007; Zhang, Qiao, Piper, & Huan, 2011).

The neighborhood-scale data also reveal a "cold spot", where low values are clustered together along Union and 10th Streets. Residential yards where the samples were collected in these areas belong to units in the Acorn Apartments, public housing that was built in 1996 after the original 1960s Acorn housing project was razed. With the new construction, original soil was likely removed and new soil and turf grass brought in during landscaping.

Site-scale

Analysis of eleven sites reveals that Pb concentrations vary significantly at the site-scale. Variability at each site was generally
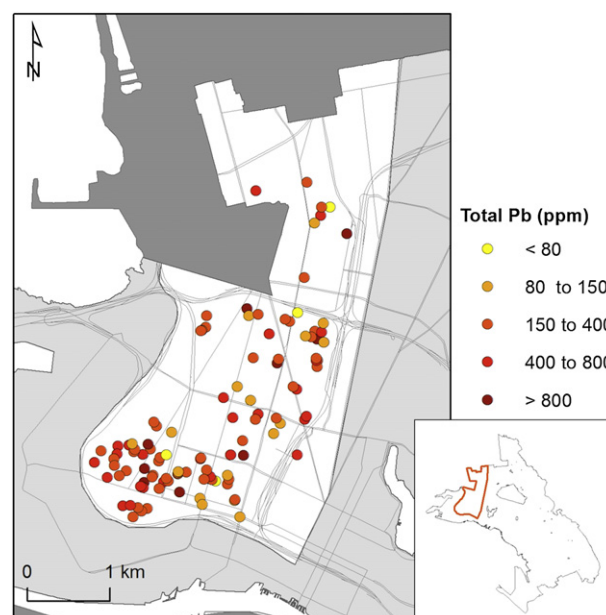

Fig. 4. Estimated total soil Pb concentrations (mg kg^{-1}) in residential yards in West Oakland (n = 116, data source: City Slicker Farms Backyard Garden Program).
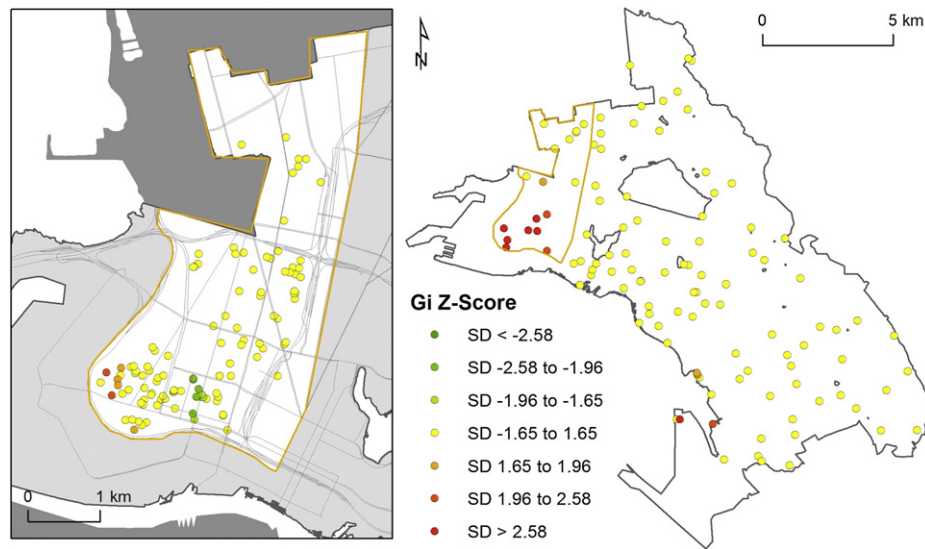
Fig. 5. A Getis–Ord G_i^* statistical "hot spot" analysis of estimated total Pb concentrations in West Oakland (left) and Oakland (right). The G_i^* score is also the standard deviation (SD) from the average value of a point's neighbors. A high z-score (red) indicates clustering of high soil Pb concentrations while a low z-score (green) indicates spatial clustering of low Pb concentrations. Median z-scores (yellow) indicate that there is no significant spatial relationship between a site's Pb concentration and that of neighboring points. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

high (see Table 4), particularly in West Oakland. As expected, Pb levels at the two West Oakland residential sites (Filbert and 9th Street, Fig. 6a and b, respectively) were much higher than EPA screening levels. These high levels are consistent with their geographic location and the age of the neighborhood, as explained in the city-scale results above. According to Sanborn Fire Insurance maps, dwellings stood on both sites as late as 1952. While clustering of elevated Pb levels at the western end of the 9th Street site do not lie on the footprint of the house, the area was littered with garbage and appears to have been used as a dumping ground in the past.

Soil Pb levels in other parts of the city were generally lower, with the exception of two sites in East Oakland, Oakport and Harbor Bay Parkway (Fig. 6e and i, respectively), both of which are located in industrial areas built on artificial fill along next to the San Leandro Bay. Maps and aerial photography indicate a century of disturbance at both sites. The Oakport site is located on East Bay Municipal Utilities District (EBMUD) land, and is managed by the East Bay

Regional Parks District as part of the Martin Luther King, Jr. Regional Shoreline. A 1918 map shows an island in the tidal flats owned by the Barbour Chemical Co. where the Oakport site is currently located (see Fig. 7a), with ownership changing hands several times over the first half of the century, before coming under EBMUD ownership. The shoreline was transformed dramatically in the late 1960s. In June 1967 the San Francisco Bay Conservation and Development Commission approved an application by the EBMUD and the Pacific Gas and Electric Corp. "for the dredging of a new and straightened channel for East Creek Slough and the filling of the old meandering channel" (Oakland Tribune, 1967). Much of the tidal wetlands were covered with fill in the 1980s, but by the early 1990s had been developed into an open space area. While the adjacent shoreline has remained the same for more than forty years, fill is occasionally added to the site. The soil at the northern end of the site (Soil 3) approached EPA screening levels, while those at the southern and central end (soils 1 and 2) were much closer to background levels (see Fig. 6f). Soils 1 and 2, which were sandier

Table 4
Total Pb (mg kg^{-1}) at selected sites throughout Oakland.

Site	Land use	Grid samples[a] (n)	Grid square size (m)	Total Pb (mg kg^{-1})			
				Mean (±S.E.)		Median	Min	Max
West Oakland								
9th St.	Vacant	7	7.52 × 7.52	1023	±126.0	1080	636	1422
Filbert	Vacant	8	7.52 × 7.52	685	±101.4	664	402	1233
Central Oakland								
Brookdale	Park	12	7.52 × 7.52	88	±8.1	86	44	131
Jungle Hill	Open space	16	7.52 × 7.52	41	±2.7	37	25	65
East Oakland								
Columbia Gardens	Park	14	7.52 × 7.52	92	±8.8	75	61	169
Doolittle	Vacant	8	30.48 × 30.48	74	±21.2	56	30	218
Harbor Bay (soil 1)	Open space	18	15.24 × 15.24	176	±40.9	113	20	536
Harbor Bay (soil 2)	Open space	8	15.24 × 15.24	221	±71.9	162	38	651
Oakport (soil 1)	Open space	12	15.24 × 15.24	4	±0.9	2	2	12
Oakport (soil 2)	Open space	6	15.24 × 15.24	3	±0.2	3	2	3
Oakport (soil 3)	Open space	10	15.24 × 15.24	175	±26.6	154	68	346
Tassafaronga	Park	6	7.52 × 7.52	107	±7.6	105	85	141
Oakland Hills								
98th Ave.	Vacant	12	7.52 × 7.52	60	±20.9	42	24	288
King's Estates	Open space	13	15.24 × 15.24	18	±1.2	19	11	26

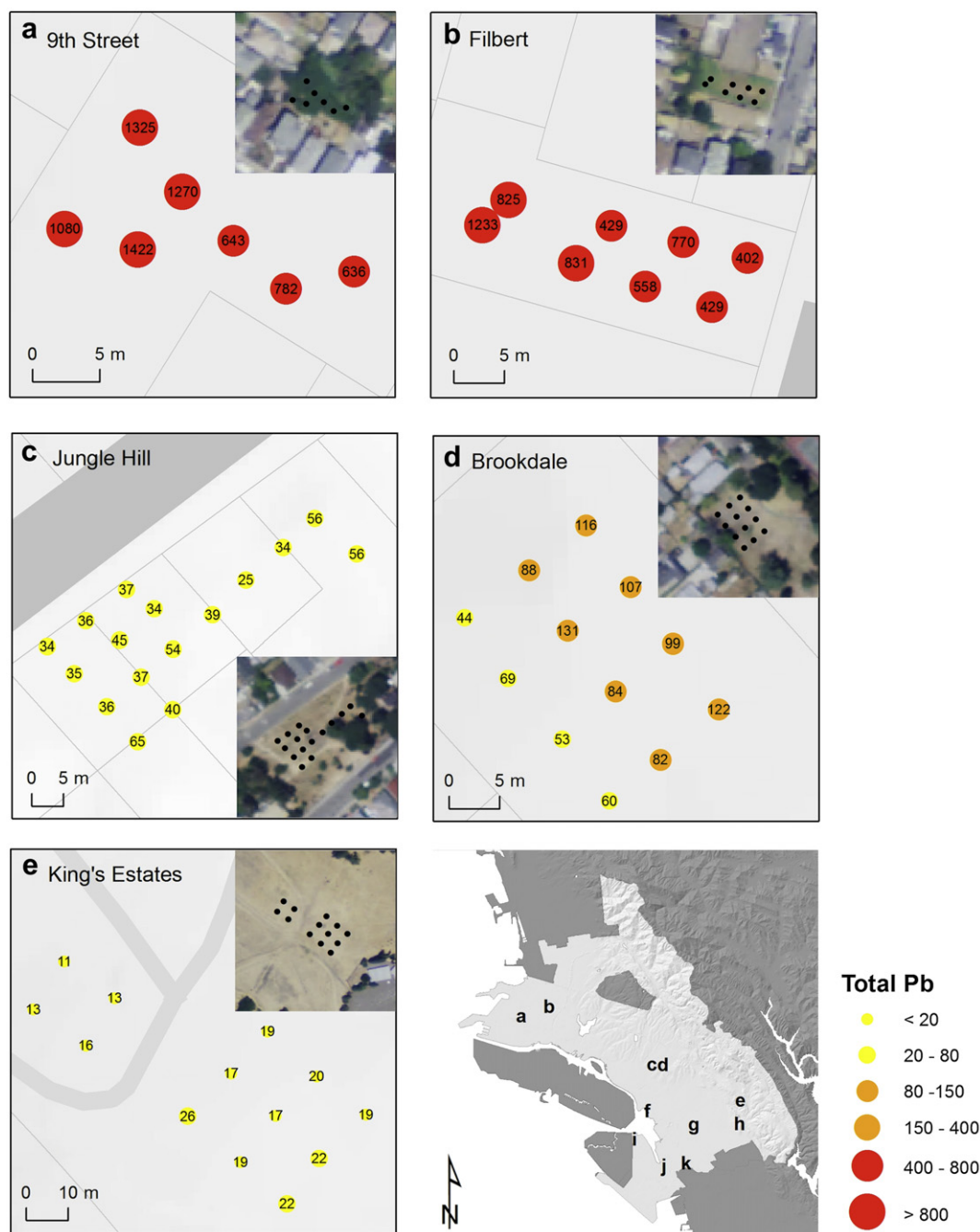[a] Each grid sample was composited from 9 soil cores.

Fig. 6. Total soil Pb concentrations (mg kg^{-1}) at eleven sites in Oakland. Each circle represents both the mean Pb value and mean center of nine soil cores (0–10 cm) taken from a grid square of 25′ × 25′ (a, b, c, d, g, h, k), 50′ × 50′ (e, f, i), or 100′ × 100′ (j). Red circles indicate Pb values above EPA screening level (400 mg kg^{-1}), orange above previous (150 mg kg^{-1}) and current (mg kg^{-1}) CHHSL Pb screening levels. Mean centers of each grid square are also represented with black dots in the inset. Sites locations are indicated on the map of Oakland (bottom right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than soil 3 (89, 82, and 67% sand, respectively), appear to have been deposited recently; During sampling, a noticeable drop in elevation (approximately 0.25 m) was visible, marking the limits of where soil 2 fill had been spread by a bulldozer. Vegetation in soil 3, including large *Baccharis* shrubs and high annual grass (*Avena barbata*), was much more established, indicating that the soil had been left undisturbed for some time. Vegetation on Soils 1 and 2 was dominated by earlier succession species such as yellow star thistle (*Centaurea solstitialis*), common in highly disturbed areas (Roché & Roché, 1991). Elevated Pb levels in soil 3 may also be related to higher clay content (14%), two to three times higher than

the other two soils, as well as to CEC (22.9 cmol$_c$ kg^{-1}), two to five times higher than the other soils.

The Harbor Bay site, owned by the Port of Oakland, lies at the north end of Oakland International Airport's historic North Field, and immediately south of the Spunkmeyer Soccer Field (see Fig. 7b). Built on artificial fill on the tidal flats of Bay Farm Island in 1927, North Field was the airport's first runway (and the longest in the world at the time of its construction, measuring 7020 feet, or 2.138 km). Aerial photographs from 1981 to 1994 show two structures on the western half of the field. In 1994, the eastern half of the site appears to have been graded, and possibly covered with
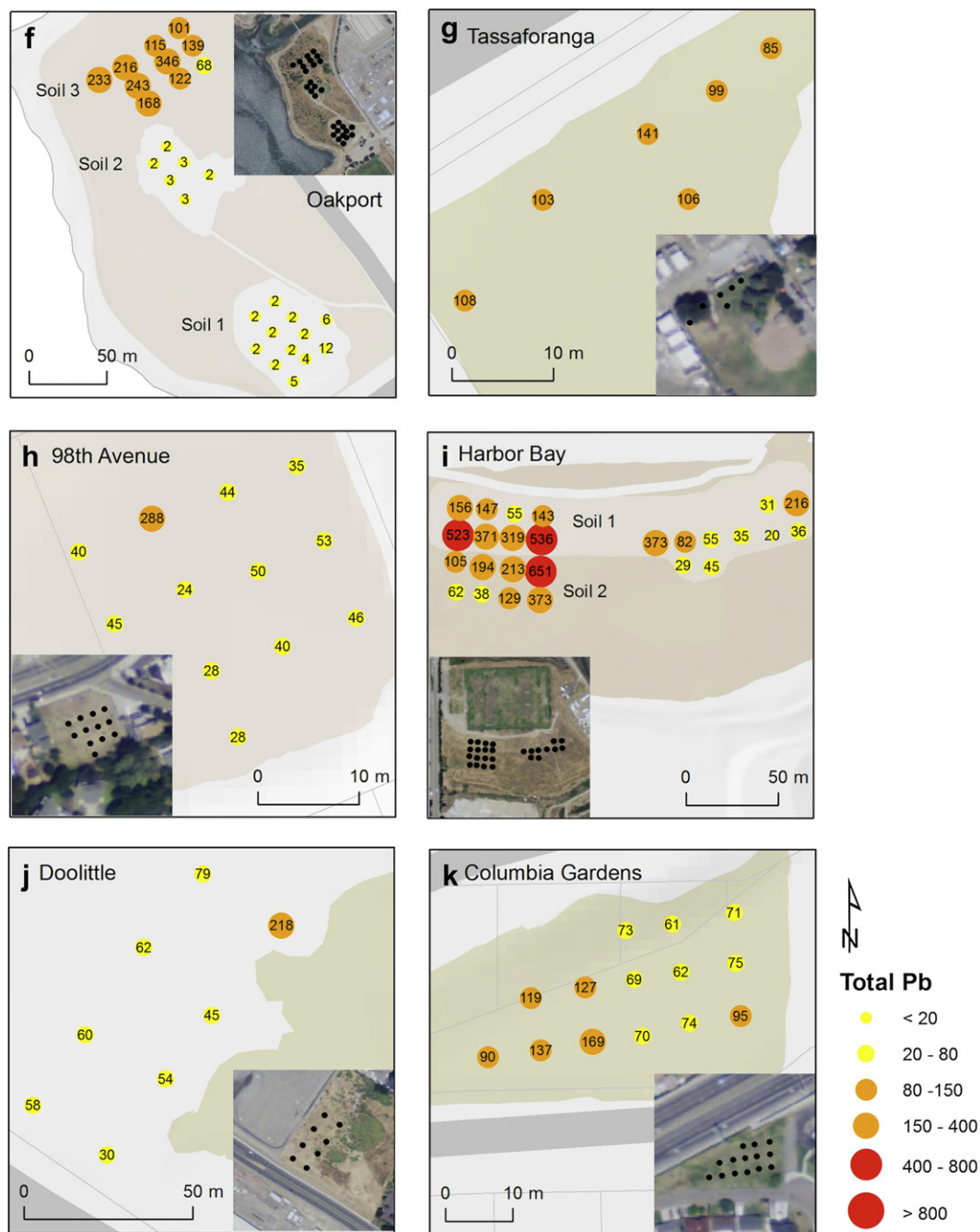
Fig. 6. (*continued*).

new fill. Elevated Pb levels appeared at the western end of the Harbor Bay site and seem to be associated with activity visible in the 1994 photo (see Fig. 6i). It appears that fill was applied on the eastern half of the site, perhaps diluting Pb concentrations. Elevated Pb concentrations are also possibly a legacy of atmospheric deposition from the adjacent Engine Test Facility. Cadmium concentrations at this site were five to ten times higher than at the other sites included in the 2009 site-scale analyses; borderline PCB presence (>50 mg kg^{-1}) was also noted. A 2005 photo also shows a difference in the soils (or possibly vegetation) on the two halves of the site, but both field sampling and the 2009 NAIP photo revealed evidence that new fill had been added on the northern half of the site (Soil 1 in Fig. 6i).

As expected, Pb levels in the three parks sampled were generally low. Since all three sites are now city parks managed by OPR, new soil and turf grass was likely brought during construction. Several houses built in the 1940s were located on the Columbia Gardens site (Fig. 6k), but were demolished in the early 2000s for the widening of 98th Avenue, a major thoroughfare linking Interstate 880 to the airport. A sound-insulating retaining wall now separates the site from 98th Avenue. Lead levels greater than 90 mg kg^{-1} were clustered at the western end of the site, but do not appear to be related to land use history. According to the 1952 Sanborn map, the Tassaforanga site (Fig. 6g) was located on vacant US Government land. At the Brookdale site (Fig. 6d), a dwelling and outbuilding were present as late as 1952, but Pb levels at the site

Fig. 7. Historical land use change in East Oakland. The 1918 map (top-left) shows the tidal flats surrounding San Leandro Bay in East Oakland. Approximate locations of the (a) Oakport and (b) Harbor Bay sites are outlined in red. Both sites received significant amounts of artificial fill during the 20th century, much of it likely dredge material from the Alameda Estuary. The East Creek Slough was filled in during the late 1960s. The Harbor Bay site (b) was repeatedly modified as evidenced in photos from 1981 (left), 1994 (center), and 2009 (right). The Engine Test Facility is visible to the right in the 1994 and 2009 images. Sources: Alameda County Chamber of Commerce (1918); City of Oakland Office of Planning (1981, 1994); National Agriculture Imagery Program, USDA (2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were relatively homogeneous and do not reflect the footprint of the buildings, likely the result of site's development as a park.

Lead levels at two open space areas, King's Estates (Fig. 6e) in East Oakland and Jungle Hill (Fig. 6c) in Central Oakland, were also low. Both sites are classified as Resource Conservation Areas by OPR, and are maintained infrequently; due to steep slopes, both sites are grazed annually by a herd of goats. Both sites appear unchanged in 1981, 1994, 2005, and 2009 aerial imagery. Lead levels at King's Estates are similar to natural background levels; indeed, the site has never been developed.

At the Jungle Hill site, geomorphology may also have played a part in low Pb levels. Massive mixing of soils following a series of landslides may have diluted whatever surface deposition of Pb had been there. The site was once home to several houses. No development appears on the 1903 map, which was made 6 years prior to the city's annexation of its eastern territory. By 1925, however, the neighborhood was well established and three houses built on the bluff above the sampling site. During the 1930s, two of the houses collapsed during a landslide. In the 1970s, the final house collapsed. The site became a park in the 1980s, first owned by the Santa Rita Community Land Trust, later ceded to OPR (Oakland Museum of California, 1997).

Finally, a high Pb concentration in one grid-square at the 98th Avenue site (Fig. 6h) is possibly a legacy of an old fire station that once stood on the property. A 1952 Sanborn Fire Insurance map shows the Engine No. 26 and Truck No. 8 station on the northeast corner of the lot in approximately the same location as the elevated Pb levels. The station was still visible in a 1994 aerial photo.

Implications for urban agriculture and environmental justice

This study attempts to answer a fundamental question: is soil Pb contamination a major obstacle to the scaling up of urban agriculture in Oakland? Based on the data presented here, it appears that the answer is no, with the exception of some areas of West Oakland or former industrial areas along San Leandro Bay.[2] Overall, total Pb levels were lower than expected, given the city's industrial past and dense freeway network. Lead levels encountered in other cities (e.g., Baltimore, New Orleans, and Boston) may be higher due to longer histories of urban development and Pb deposition from industry, traffic, and old housing stock. Lead levels reported in those cities are generally much higher than those found in Oakland. In Rust Belt cities, where urban agriculture is spreading rapidly across a post-industrial landscape of vacant lots, the risk of soil Pb levels at potential urban agriculture sites may also be greater than in Oakland. Finally, it is also possible that low Pb levels are a result of sampling depth (0–10 cm). While we followed standard sampling protocol for geochemical mapping under the assumption that soil would be homogenized to a depth of 10–15 cm during agricultural tillage, surface deposition of Pb would have been diluted.

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[2] The EPA recently launched a two-year Emergency Response project to remediate more than a hundred residential yards in the South Prescott neighborhood of West Oakland. The innovative remediation approach involves amending soils (which average > 800 mg kg^{-1}) with fishbone meal, a hydroxyapatite that complexes with soluble Pb to form the highly recalcitrant pyromorphite (Barringer, 2011; Seltenrich, 2011).

Given the low Pb levels, one might argue that such an assessment was a waste of time or resources. On the contrary, assessing these sites for Pb was not an errant mission but a necessary and precautionary first step in an ongoing effort to expand urban agriculture on Oakland's vacant land. Indeed, Pb levels are high at many sites. Our analysis captured some broad spatial trends as well as some site-specific trends. This study further documents the uneven distribution of pollutants across the urban landscape, disproportionately impacting low-income populations of color. West Oakland, with its long industrial, age and condition of its housing stock, and long legacy of pollution and vibrant environmental justice movement that arose in response (Costa et al., 2002; Walker, 2007), bears the brunt of this burden. This study reveals that the highest concentrations lie in the Lower Bottoms and South Prescott neighborhoods, in particular.

While these larger-scale trends indicate an uneven distribution of soil Pb pollution in Oakland, soil sample data and land use histories from individual sites should be closely scrutinized before urban agriculture is practiced at a particular site. As the neighborhood-scale data reveal, the range of soil Pb concentrations at a given site can be incredibly wide and levels at sites dangerously high. Furthermore, assessment of other heavy metals (notably As, Cd, Ni, and Zn) should factor alongside Pb during the planning process. Broad-based screening for organic contaminants such as PCBs and PAHs can be very expensive, and should therefore be done on a site-specific basis, based on knowledge of previous industrial contamination at or near the site.[3]

Conclusions

In addition to characterizing Pb contamination at potential food production sites throughout the city, this research also helps to identify key trends that may be of use to urban agriculture advocates as they consider where to initiate new projects. First, geography matters; soil Pb concentrations in our study were highest in West Oakland (the oldest part of the city) and lowest in the Oakland hills. Second, land use has a significant effect on Pb levels. Soil Pb tended to be higher in gardens and vacant lots, and lower in parks and late-succession open space. Furthermore, analysis of spatial clustering at city- and neighborhood scales combined with land use histories at the site-scale were able to highlight the relationship between certain land use histories and soil Pb levels that were validated at the site-scale. Third, the city's zoning classifications (which are tied to land use at a coarser level) also affect soil Pb concentrations. In this study, soil Pb tended to be higher in residential and industrial zones than in open space. Finally, this research underscores the importance of scale when assessing contamination. While mapping contamination at city-scale or neighborhood scale can ultimately reveal geographic trends, assessing risks associated with Pb contamination must ultimately be carried out at individual sites, given the significant variability of soil Pb concentrations at the site-level. As stakeholders move forward with the promotion of urban agriculture on vacant lots, such a precautionary multi-scalar assessment can shed light not only on potential contamination risks at a particular site, but can also elucidate the uneven and inequitable distribution of contaminant burdens across a socioecological landscape.

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[3] A preliminary assessment of a sub-sample of 11 sites using Dexsil Clor-N-Soil PCB screening kits revealed no significant PCB presence. Nevertheless, further assessment of these sites and others would be prudent.

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