

Management Options for Contaminated Urban Soils to Reduce Public Exposure and Maintain Soil Health

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Abstract

Soil management in urban areas faces dual challenges of reducing public exposure to soil contaminants, such as lead (Pb) and polycyclic aromatic hydrocarbons, and maintaining soil function. This study evaluated three management options for an urban lot in Cleveland, OH, containing 185 to 5197 mg Pb kg⁻¹ and 0.28 to 5.50 mg benzo(a)pyrene kg⁻¹. Treatment options included: (i) cap the site with a soil blend containing compost and beneficially reused dredged sediments, (ii) mix compost with the soil, and (iii) mix compost and sediments with the soil. The soil blend cap reduced surface soil Pb to 12.4 mg Pb kg⁻¹ and benzo(a)pyrene content to 0.99 ± 0.41 mg kg⁻¹. Aggregate stability for 2- to 0.25-mm aggregates in the soil blend cap was 13% compared with the 38% aggregate stability in the urban soil. Mixing compost with the soil reduced benzo(a)pyrene content, but sample variability indicated that elevated spots likely remained exposed at the surface. Compost addition diluted soil Pb and increased aggregate stability to 60%. Mixing compost and sediments with the soil was the only management option accomplishing both management goals of reducing surface soil contaminants and maintaining soil health. For this combined mixing option, aggregate stability was 37%, soil Pb was 15 mg kg⁻¹, and benzo(a)pyrene was 0.99 ± 0.09 mg kg⁻¹. Food-grade oil addition did not increase benzo(a)pyrene degradation. Future studies should evaluate how incorporating soil blends in different soil types with a range of contaminants may offer a suitable long-term management option for urban soil contaminants.

Core Ideas

- Soil blend incorporation maximized soil health and human health benefits.
- Soil capping may cover contaminants but reduced surface soil aggregate stability short term.
- Compost addition maintained surface aggregate stability and diluted Pb surface contamination.
- Incorporating soil blends offers a potential long-term urban soil management solution.

SOILS in cities tend to have increased polycyclic aromatic hydrocarbon (PAH) and lead (Pb) concentrations relative to soils sampled from rural areas. When these contaminants are encountered, the public and regulators need to manage these soil contaminants, particularly since several PAHs, including benzo(a)pyrene (BaP), are carcinogenic, and Pb is a neurotoxin. Polycyclic aromatic hydrocarbons originate from incomplete combustion and could come from a variety of sources, including former trash burn piles, automobile exhaust, coal residue, or gasoline spills. Lead can originate from several sources, including Pb-based paint, leaded gasoline, Pb pipes, historic smelter wastes, and other mining wastes.

Soil background PAH levels can range from 5 to 120 µg kg⁻¹ in rural areas to 0.06 to 31.2 mg kg⁻¹ in cities (Sims and Overcash, 1983; Bradley et al., 1994; Saliene et al., 2002; Rabideau et al., 2007; Nam et al., 2008; Nathanail and Ogden, 2013). Soil Pb is similarly elevated in urban soils. Total soil Pb concentration ranged from 20 to 2250 mg kg⁻¹ in Cleveland, OH, and many soils were above the 400 mg kg⁻¹ USEPA Pb screening level for residential soils (Minca et al., 2013). Twenty percent of soils sampled in and around Baltimore, MD, had concentrations >421 mg kg⁻¹, and 40% of samples were >150 mg kg⁻¹ (Mielke et al., 1983). Twenty-five percent of soil samples collected in Oakland, CA, were >150 mg Pb kg⁻¹ (McClintock, 2012). In New York City, median soil Pb values were 355 mg Pb kg⁻¹, and the mean was 600 mg Pb kg⁻¹ (Cheng et al., 2015).

Managing these contaminants depends on how the concentrations are evaluated with regard to soil screening levels. Screening levels for Pb and PAHs are currently established for total concentration and assume the person is in direct contact with bare soil. For example, the Ohio Voluntary Action Program (VAP) standards (OAC 3745-300-08) include several PAHs, including a standard of 1.2 mg BaP kg⁻¹ for the residential, direct soil ingestion pathway. The USEPA screening levels for BaP carcinogenic effects is 0.016 mg kg⁻¹ and for soil ingestion is 0.021 mg kg⁻¹ (USEPA, 2016). While the current USEPA soil Pb screening level for bare soil that children have access to is 400 mg kg⁻¹, the USEPA may lower this limit to 150 mg kg⁻¹ (Henry et al., 2015). As indicated above, background Pb and PAH concentrations in urban soils can be greater than current and proposed soil screening levels.

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Abbreviations: BaP, benzo(a)pyrene; PAHs, polycyclic aromatic hydrocarbons; POXC, permanganate oxidizable carbon; QuEChERS, Quick Easy Cheap Effective Rugged Safe; TEFs, toxicity equivalency factors; UPLC, ultra-performance liquid chromatography; VAP, Voluntary Action Program.

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Although these screening levels are exceeded, multiple research studies suggest that PAHs in soil have soil ingestion bioaccessibility <50%, and this finding indicates that bioaccessibility assessment may be included in site-specific risk assessments rather than relying on total contamination concentration only (Ruby et al., 2016). Bioaccessibility refers to the amount of contaminant extracted in a laboratory test (in vitro) that can be used to estimate the contaminant uptake that would occur in an animal study (Ruby et al., 2016). Bioavailability refers to the amount of contaminant measured in an animal uptake study (in vivo), and this contaminant amount can be described in absolute concentration or a concentration relative to a standard contaminant material (Ruby et al., 2016). With well-established regression equations between bioaccessibility and bioavailability data, bioaccessible tests can be used to help predict contaminant uptake in a variety of new soils without conducting in vivo studies for each new soil. A similar approach for managing Pb using site-specific data regarding soil Pb bioaccessibility has been proposed by Henry et al. (2015) to identify potential soils where standard soil bioavailability assumptions could be modified. Adopting bioavailability-based screening levels could reduce the amount of soil recommended for complete soil removal. There is no universally accepted screening level for total or bioavailable Pb or PAHs in soils. Current soil screening levels can vary among political boundaries, such as occurs within the northeastern United States (Enander, 2014).

While soils in cities may have elevated contaminant concentrations, less disturbed soils in cities may have desirable soil properties, including reduced bulk densities, higher biological activity, and increased soil organic matter (Scharenbroch et al., 2005). Management strategies for contaminated urban soils should enhance existing soil properties and reduce soil contaminant exposure levels. Some of these strategies could include adding materials to the site, such as composts and noncontaminated soils. Soil removal would potentially reduce soil contaminant exposure levels without enhancing the existing soil properties that would be lost when the soil was removed. Removed soil would also create a disposal issue and increase remediation costs for the landowner. Research continues into quantifying soil contaminant levels within the context of physical, chemical, and biological properties to more comprehensively evaluate soils (Dawson et al., 2007; Volchko et al., 2014; Carlson et al., 2015).

Using soil blends is a management strategy that could potentially accomplish goals of both enhancing soil functions and reducing soil contamination (Sloan et al., 2012). Soil blends, also known as manufactured soils, can use a variety of materials including composts and beneficially reused materials to improve soil properties and reduce contaminants (Wallace and Terry, 1998). For the purposes of this study, a soil blend is defined as a mixture of materials intended to function as the topsoil of a mineral soil. Depending on their end use, these mixtures can contain composts, sand, silt, clay, other mineral soil removed from another location, or coarser aggregates (Sloan et al., 2012). Improving some soil properties could reduce contaminant remediation success, depending on soil contaminant properties. For example, a well-aggregated, PAH-contaminated soil could physically protect PAHs from degradation (Amellal et al., 2001). Adding organic matter can improve soil properties, but this addition can also increase possible sites for PAHs to sorb

to the organic matter and become less available for degradation (Alexander, 2000; Cornelissen et al., 2005). This increased PAH sorption could decrease PAH bioavailability but would not reduce the total PAH contaminant concentration. Depending on how soil screening levels are applied to the soil in question, the soil would either be fixed (from a bioavailability assessment) or remain a problem (from a total contaminant assessment). This organic matter can also increase sorption sites for phosphorus (P) (Withers and Sharpley, 1995) and Pb (Zimdahl and Skogerboe, 1977; Basta et al., 2005), and this could reduce the likelihood for remediating soil Pb by forming less soluble Pb-P minerals, such as chloropyromorphite [$\text{Pb}_5(\text{PO}_4)_3\text{Cl}$] and hydroxypyromorphite [$\text{Pb}_5(\text{PO}_4)_3\text{OH}$] (Scheckel et al., 2013). On some studied soils, compost and P amendments can reduce in vitro bioaccessible Pb (Brown et al., 2005; Attanayake et al., 2014), and decreases are more pronounced with higher extraction solution pH, such as pH 2.2 or 2.5 compared with pH 1.5 (Attanayake et al., 2014; Obrycki et al., 2016).

Surfactants can be used to increase PAH availability for microbial degradation, including vegetable oils (Yap et al., 2010) and Brij 30 (a glycol ether) (Lladó et al., 2013). However, surfactants can sometimes reduce the populations of beneficial microorganisms needed for PAH degradation (Lladó et al., 2013). Additionally, oil treatments have been evaluated using a range of methods, including column extractions, batch processing, and slurry reactors, on both spiked and field-contaminated soils (Yap et al., 2010). Oil addition to field-contaminated soils in non-slurry situations was not identified by Yap et al. (2010) as a previously studied treatment option. Oil addition for enhanced PAH degradation is an ongoing field of study that requires additional testing and validation (Yap et al., 2010). The study presented here provides useful data for oil addition on field-contaminated urban soils as a potential method to reduce PAH concentrations.

Remediating soils in urban areas consists of treating smaller parcels of land, such as a residential yard. Several management options exist, including (i) using a soil blend as a capping mechanism, (ii) mixing compost into the soil, (iii) mixing soil blends into the soil, or (iv) complete soil removal. When asked about their acceptance for soil capping, the public indicated lower levels of acceptance for this option compared with other treatment options (Obrycki et al., 2017). Both the public and regulators were willing to consider bioavailability adjustments for contaminants (Obrycki et al., 2017). Complete removal of the topsoil from the yard for ex situ treatment is likely not feasible for the landowner or cost effective for all parcels above soil screening levels. This option would also eliminate any existing beneficial soil properties, such as increased organic matter and aggregate stability that can occur in undisturbed urban soils.

Given the widespread occurrence of Pb and PAHs as urban soil contaminants, this project evaluated treatment practices that could be implemented by the public to reduce soil contaminant hazards in yard soils. The three practices included: (i) applying a surface cap of sediment + compost, (ii) mixing compost directly into the soil, and (iii) mixing both sediment and compost into the soil. This study combined soil remediation and soil health research using beneficially reused Lake Erie harbor sediment from the Cleveland harbor, an urban soil from Cleveland, and readily accessible composts. Food-grade vegetable oil was evaluated as an extra substrate for microbial activity and a PAH surfactant agent. This

study provides novel research regarding the suitability of accessible soil management options for widespread soil contaminants in urban areas to address soil contaminant and health properties.

Materials and Methods

Soil and Sediment Materials

Dredged sediments came from confined disposal facilities in Cleveland. Two sediment materials were used: Sediment A, collected from a location expected to have higher PAH concentrations, and Sediment B, collected from an area where PAH levels were anticipated to be lower. Existing data collected by the operators of the confined disposal facilities informed these sampling locations. Previously collected preliminary data indicated that the harbor sediment had pH 7.4, sandy loam texture, 28 mg Pb kg⁻¹, and individual PAH concentrations ranging from 200 to 1000 µg kg⁻¹. The soil material was collected from a residential yard in Cleveland. This site consisted of adjacent vacant lots from building demolitions comprising 683 m² (7350 ft²). Preliminary sample analysis indicated that soil contained 600 to 700 mg Pb kg⁻¹ and that one location had 5197 mg Pb kg⁻¹. Soil had a silt loam texture and individual PAH concentrations between 2000 and 4000 µg kg⁻¹. Two compost materials were used. Compost A was a biosolids mix (“ComTil”) produced by the City of Columbus containing composted biosolids, yard waste, and wood chips. Compost B was a mixture of manure, coffee grounds, and yard waste processed by Price Farms Organics. Presented tables denote Compost A as “biosolids” and Compost B as “manure.” The City of Columbus biosolids is exceptional quality and is managed following USEPA Part 503 regulations and Ohio Administrative Code (2016) (OAC) 3745-50. Price Farms Organics is an Ohio EPA licensed class 2 composting facility and meets standards for compost products, as outlined by OAC 3745-560-230. Supplemental Table S1 includes nutrient and contaminant analysis provided by the suppliers.

Soil Treatments

The components were mixed together to evaluate three treatment options: (i) creating a surface cap of sediment + compost, (ii) adding compost to the soil, and (iii) incorporating compost and sediments into the soil (Table 1). Each treatment option was evaluated in separate containers. This study design screened a range of amendment combinations to identify possible treatments for further evaluation. Components were added on an equal-volume basis using a measured scoop. Rates were intended to reach an approximate 1:1 soil–sediment:compost ratio, except for the combined incorporation option that used equal volumes of all three source components (soil, sediment, and compost). Dry weight mixing ratios are included in Table 1. This combined treatment option used equal volumes of sediment A and B and compost A and B to evaluate a comprehensive mixture of all components. Treatments included an oil-added option to evaluate the potential of food-grade vegetable oil to enhance PAH degradation. Food-grade vegetable oil, as purchased from grocery stores, is a publicly available soil blend component; however, the economics of widespread oil addition were not directly considered by this study. Food-grade vegetable oil application rates were informed by Yap et al. (2010), who identified previous studies adding oil at a 1 to 5% mass ratio to soils when trying to degrade PAHs in soils.

Soil chemical and biological properties were also compared between oil and non-oil treatments to evaluate if the oil addition affected soil treatments beyond affecting PAH concentrations only. Mass data in Table 1 are presented on a 105°C oven-dried soil basis to account for the water mass in compost.

Soils were mixed by hand and incubated for 21 wk (October 2015–March 2016) in a laboratory. Weekly, soils were watered with deionized water and stirred by hand. Soils were watered to maintain approximately 30 to 40% gravimetric moisture content. Soils were allowed to dry between the weekly watering occurrence to simulate wetting and drying cycles that might occur in a field setting. After the 21-wk incubation process, soils were air dried and sieved to <2 mm. Containers had a capacity of 13.25 L and were 29.21 cm wide, 38.74 cm deep, and 18.42 cm tall. After the 21-wk incubation, three subsamples from each container were evaluated for soil properties, including soil Pb analysis, and two subsamples were evaluated for PAHs to generate an estimate for the individual container. The number of subsamples were selected to provide additional information about the range of measured soil properties for each container. The number of PAH subsamples were lower due to the cost of PAH analysis relative to the other measured soil properties. When individual container results are presented, the average of the subsamples is reported with a standard error of the mean. To avoid pseudoreplication, statistical analysis was not performed among individual containers and was only performed when multiple containers were grouped together and compared with other container groups.

Evaluated Soil Properties

For physical properties, soil texture (Kettler et al., 2001) and aggregate stability for 2.0- to 0.25-mm aggregates (Moebius-Clune et al., 2016) were evaluated. Tested biological properties included organic carbon (C) (Heanes, 1984), permanganate oxidizable carbon (POXC, referred to as active C) using the recommended 2.5-g soil (Weil et al., 2003), and 4-d soil C mineralization (respiration) (Moebius-Clune et al., 2016). Chemical properties included pH (1:1 soil:water ratio) and Mehlich-3 extractable elements (Mehlich, 1984). Organic C extraction used a CEM-MARS 5 (CEM Corporation) and was quantified with a Genesys 10 spectrophotometer (Thermo Electron Corporation) set at 600 nm. Active C was quantified using the same spectrophotometer set at 550 nm. Soil nutrient extracts, including soil Pb, were analyzed using ICP-OES (Varian 720). Quality control for the ICP-OES included blanks, blank spikes, composite dilution, composite spikes, and check standards. Soil pH was measured using an accumet pH probe (Fisher Scientific) that was calibrated in pH 2.0, 4.0, 7.0, and 10.0 standards. Mehlich-3 soil Pb values estimated total Pb using the regression equation from Minca et al. (2013) for soils with concentrations of 0 to 1200 mg Pb kg⁻¹. This regression equation was developed using soils primarily from Cleveland and correlated total soil Pb, as determined using acid digestion (USEPA Method 3051a) and the Mehlich-3 extracting solution. Because the contaminated soil was collected from the same region, the regression equation was used to estimate total soil Pb.

PAH Assessment

Selected soil samples were analyzed for PAHs by ALS Environmental (Cincinnati, OH), using USEPA Method 8270

Table 1. Soil treatment options, including capping, composting, and incorporation.

Treatments‡	Compost	Oil	Soil†	Compost†	Oil	Soil:compost mass ratio	Soil:oil mass ratio	Soil:compost volume ratio
g								
Capping								
SA	A (biosolids)	None	6356	720		8.8		1:1
SA	A	+	6381	662	406	9.6	15.7	1:1
SA	B (manure)	None	6382	534		12.0		1:1
SA	B	+	6254	589	390	10.6	16.0	1:1
SB	A	None	5305	939		5.6		1:1
SB	A	+	5536	912	380	6.1	14.6	1:1
SB	B	None	5543	550		10.1		1:1
SB	B	+	5204	676	347	7.7	15.0	1:1
Compost addition only								
Soil	None	None	3331					
Soil	A	None	3473	886		3.9		1:1
Soil	A	+	3198	798	270	4.0	11.8	1:1
Soil	B	None	3198	685		4.7		1:1
Soil	B	+	3207	599	240	5.4	13.4	1:1
Incorporating capping into soil								
SA + SB + Soil	A + B	None	3243	3012		§	§	1:1:1§
SA + SB + Soil	A + B	+	3251	2934	339	§	§	1:1:1§

† Expressed on an oven-dried basis.

‡ Materials used were Sediment A (SA), Sediment B (SB), and soil-urban soil.

§ For the combined-treatment scenario, this compost addition included equal parts Compost A, Compost B, Sediment A, and Sediment B. Given this combined addition, the ratios were not calculated.

(USEPA, 2014). Polycyclic aromatic hydrocarbons were also evaluated using the Quick Easy Cheap Effective Rugged Safe (QuEChERS) method using acetonitrile as the extracting solution following Thermo Scientific Application Note 20677 (Khan, 2014). Five grams of 105°C oven-dried, 2-mm sieved soil, 5 mL of deionized water, and 10 mL of acetonitrile (Fisher Scientific, CAS 75-05-8) were combined in a 50-mL centrifuge tube. Solution was shaken and vortexed. Next, 4 g of MgSO₄ and 1 g NaCl were added and the solution was shaken for 10 min and centrifuged for 10 min at 2500 rpm. Supernatant (1 mL) was transferred to the dispersive solid phase extraction cleanup tubes, shaken for 5 min, vortexed, and centrifuged again at 8000 rpm. Approximately 0.6 mL of the supernatant was transferred to 2-mL glass vials. Each incubation treatment was evaluated in duplicate. Samples were analyzed in batches of 10 vials for ease of sample handling.

Samples were analyzed using an Ultra-Performance Liquid Chromatography (UPLC) Waters Acquity H-Class 1200 (Waters Corporation, H-Class) with a Waters ACQUITY BEH Shield RP18 2.1-mm × 150-mm (part no. 186003376) column. Sample gradient consisted of HPLC-grade acetonitrile (Fisher Scientific, CAS 75-05-8) and HPLC-grade deionized water (Fisher Scientific, CAS 7732-18-5). Instrument settings followed Waters Polynuclear Aromatic Methods 550.1, 610, and 8330 (Waters Corporation, 2016). Analytical conditions included a column temperature of 45°C, an injection volume of 2 µL, and a flowrate of 0.6 mL min⁻¹. Data were collected and quantified using Empower 3 software (Waters Corporation, 2010). Photodiode array data were collected at 254 nm and fluorescence detection data were gathered at timed excitation and emission wavelength changes. The following 15 PAHs were characterized: acenaphthene, anthracene, benzo(a)anthracene,

BaP, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, chrysene, dibenz(a,h)perylene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, naphthalene, phenanthrene, and pyrene. Retention times were compared across samples to ensure similar peak identification.

Calibration standards were made using a stock of 10 µg mL⁻¹ for each PAH in acetonitrile (AccuStandard, drug identification no. 38414-23 PAHs). Check standards were made diluting a 0.5-mg mL⁻¹ BaP standard (AccuStandard, M-8310-FL-05). Individual standards for all 15 analyzed PAHs at a 0.5-mg mL⁻¹ concentration (AccuStandard) verified peak retention times during initial method testing. Blanks and spiked samples evaluated the extraction technique and recoveries.

Data were analyzed using Minitab (Minitab, 2010) and Microsoft Excel 2010. Paired *t* tests compared treatment effects (oil vs. non-oil amended, Compost A vs. Compost B, Sediment A vs. Sediment B). Toxicity equivalency factors (TEFs) relative to BaP (Nisbet and LaGoy, 1992) were calculated for the urban soil samples sent to ALS Environmental.

Results and Discussion

Soil Physical Properties

When compared with untreated controls, soil management options altered soil physical, chemical, and biological properties. Surface-capping treatments reduced surface soil aggregate stability from 38% in the control urban soil to 13 ± 3%. Sediments A and B were predominantly sand (Table 2) and had 1 and 5% aggregate stability, respectively. According to the aggregate stability test methods, all sand particles >250 µm are not counted as stable aggregates. In contrast, the urban soil control contained 36% silt, 10% clay, 5.4% soil organic C, and 38% 2- to 0.25-mm stable aggregates. Across all four treatments, the compost-treated

Table 2. Soil health test results for treatment options.

Treatments	Texture	pH (1:1)	Active carbon	Respiration	Organic carbon	Stable aggregates‡
	% sand; % clay	standard unit	mg POXC† kg ⁻¹	mg CO ₂ g ⁻¹	— % —	
Capping						
Sediment A (SA)	95; 1	7.62 ± 0.1	30 ± 17	0.1 ± 0.0	0.6 ± 0.0	1
SA + Compost A (biosolids)		7.33 ± 0.1	411 ± 12	0.4 ± 0.2	2.6 ± 0.2	10
SA + Compost A + oil		7.91 ± 0.1	544 ± 10	2.6 ± 0.2	4.1 ± 0.0	15
SA + Compost B (manure)		8.02 ± 0.1	580 ± 9	0.7 ± 0.0	1.9 ± 0.1	4
SA + Compost B + oil		7.82 ± 0.1	503 ± 8	1.8 ± 0.1	4.1 ± 0.3	8
Sediment B (SB)	85; 4	7.54 ± 0.1	151 ± 16	0.2 ± 0.1	0.9 ± 0.0	5
SB + Compost A		7.53 ± 0.1	814 ± 11	0.9 ± 0.0	3.0 ± 0.2	17
SB + Compost A + oil		8.23 ± 0.1	516 ± 16	2.5 ± 0.0	4.0 ± 0.1	31
SB + Compost B		7.66 ± 0.1	777 ± 17	0.9 ± 0.1	3.7 ± 0.1	9
SB + Compost B + oil		7.66 ± 0.1	673 ± 90	2.3 ± 0.1	4.9 ± 0.1	12
Compost addition only						
Urban soil	54; 10	6.82 ± 0.1	506 ± 4	0.8 ± 0.0	5.4 ± 0.0	38
Soil + Compost A		6.90 ± 0.1	934 ± 22	1.4 ± 0.0	11.1 ± 0.1	57
Soil + Compost A + oil		6.96 ± 0.1	904 ± 19	2.8 ± 0.1	12.3 ± 0.1	68
Soil + Compost B		7.14 ± 0.1	989 ± 30	2.4 ± 0.1	11.1 ± 0.2	48
Soil + Compost B + oil		7.06 ± 0.1	910 ± 13	2.6 ± 0.1	12.0 ± 0.2	67
Incorporating Cap Into Soil						
All components		7.06	571 ± 15	1.0 ± 0.1	4.4 ± 0.1	31
All components + oil		7.22	465 ± 9	3.1 ± 0.1	5.4 ± 0.1	43

† POXC, permanganate oxidizable carbon.

‡ 2- to 0.25-mm aggregates.

urban soils increased aggregate stability to an average of 60 ± 5%. If other materials were used for the soil-capping treatment, surface soil aggregate stability could be increased. When using soil capping as a treatment, evaluations should include these physical soil properties, as opposed to soil contaminants only, to identify potential soil physical limitations.

Three experimental factors may have reduced aggregate formation across all the treatments. First, soils were mixed each week, and this mixing action could have disrupted aggregate stability that may have occurred if these treatments were applied in an outdoor environment and were undisturbed. Second, incubation containers were not allowed to drain, and this reduced drainage caused salts to remain within the soil rather than be washed out, as would more likely occur in an outdoor application setting. These salts, particularly sodium (Na) if it were present in high quantities, could have reduced aggregate formation. Third, the 21-wk incubation period was not necessarily a sufficient length of time for aggregates to form in the sediments, as established soil structure in dredged-sediment amended soils might not occur for up to 30 yr (Schneider and Schröder, 1995).

Soil Biological Properties

As expected, the compost within the soil treatments increased soil biological activity, as indicated by active C, respiration, and organic C (Table 2). For example, active C measurements across Sediment A treatments were 510 ± 36 mg POXC kg⁻¹, a 17-fold increase over the Sediment A control. Sediment B treatments' active C measurements were 695 ± 67 mg POXC kg⁻¹, a 4.6-fold increase over the Sediment B control. Urban soil active C was 934 ± 19 mg POXC kg⁻¹, a 1.8-fold increase over the soil control. Organic C was 1.3 ± 0.4% lower in the non-oil treatments compared with the oil treatments ($p < 0.0005$). Oil treatments

had respiration values 1.4 ± 0.7 mg CO₂ g⁻¹ higher than the non-oil treatments ($p = 0.001$). Active C did not differ between oil and non-oil groups ($p = 0.146$). These findings suggest that the permanganate extraction was not extracting the added oil C, but soil microbes were able to access the added oil C.

Soil Chemical Properties

Soil pH remained within ±1 pH unit of control soils (pH 7.62 standard units for Sediment A, 7.54 standard units for Sediment B, and 6.82 standard units for urban soil) (Table 2). Sediment A and sediment B tended to have sufficient plant nutrients, as measured by Mehlich-3 and compared with general crop recommendations (Table 3). For brevity, results from oil-added treatments are not shown. Sediment A and B controls could be limited in potassium because concentrations were below the 88-mg kg⁻¹ critical soil test threshold for several crops in the Ohio region (Vitosh et al., 1995). Phosphorus in Sediments A and B was above the 15-mg kg⁻¹ critical value for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] in the Ohio region, but Sediment A was below the 25-mg kg⁻¹ critical value for wheat (*Triticum aestivum* L.) and alfalfa (*Medicago sativa* L.) production (Vitosh et al., 1995). Micronutrients were sufficient for copper, manganese, and zinc when compared with soil test recommendations (Table 3). The micronutrient recommendations from Vitosh et al. (1995) were developed using more acidic extractions (0.1 or 1.0 M HCl) than the Mehlich-3 test used in this study. Compost addition increased nutrient values above recommendations, except for copper (Table 3). The urban soil control did not have limiting nutrients for plant growth and supported lawn cover prior to site sampling. Although Sediments A and B tended to have sufficient Mehlich-3-extractable nutrients, the high concentration of sand in both sediments and the

Table 3. Mehlich-3-extractable nutrients and lead (mg kg⁻¹) for treatment options.

Treatments	Ca	Cu	Fe	K	Mg	Mn	P	Pb	Zn
	mg kg ⁻¹								
Capping									
Sediment A (SA)	978 ± 56	8 ± 0	223 ± 10	49 ± 8	80 ± 1	47 ± 1	20 ± 1	5 ± 0	13 ± 1
SA + Compost A (biosolids)	1847 ± 96	5 ± 0	193 ± 0	465 ± 44	248 ± 12	24 ± 1	603 ± 22	4 ± 0	57 ± 2
SA + Compost B (manure)	1930 ± 61	5 ± 0	112 ± 3	888 ± 54	248 ± 6	27 ± 1	189 ± 4	3 ± 0	20 ± 1
Sediment B (SB)	1967 ± 22	11 ± 0	292 ± 5	64 ± 2	129 ± 1	56 ± 1	30 ± 0	7 ± 0	18 ± 2
SB + Compost A	2691 ± 42	6 ± 0	289 ± 3	510 ± 11	273 ± 5	35 ± 0	715 ± 8	6 ± 0	71 ± 1
SB + Compost B	2656 ± 55	6 ± 0	219 ± 5	930 ± 5	250 ± 1	40 ± 1	179 ± 2	6 ± 0	23 ± 1
Compost Addition Only									
Urban soil	2185 ± 12	27 ± 0	243 ± 2	308 ± 8	242 ± 2	29 ± 0	427 ± 1	228 ± 1	103 ± 0
Soil + Compost A	2824 ± 173	9 ± 0	241 ± 3	1028 ± 4	445 ± 4	38 ± 0	900 ± 24	89 ± 3	127 ± 4
Soil + Compost B	2564 ± 15	13 ± 0	193 ± 2	1799 ± 12	450 ± 3	45 ± 0	429 ± 1	152 ± 1	97 ± 1
Incorporating Cap Into Soil									
All components	2465 ± 10	14 ± 0	264 ± 0	632 ± 4	257 ± 3	47 ± 0	492 ± 4	4 ± 1	78 ± 1
Reference soil test sufficiency values		20†	1‡	88–150†	50‡	24†	15 and 25†		12†

† Reference values taken from Vitosh et al. (1995). Values for Cu, Mn, and Zn are the highest reported values in the associated fertilizer recommendation tables. Ranges for K depend on soil cation exchange capacity, and *p*-values are for two different crop types.

‡ Reference values taken from Zhang et al. (2017). Values included in the table are reported as the lowest concentrations that indicate potential insufficient micronutrients.

associated reduced water holding capacities would likely be primary causes for reduced plant growth prior to any potential nutrient limitations. Comparing treatments with and without oil paired by soil-sediment and compost type, Mehlich-3 P was 236 ± 120 mg kg⁻¹ higher in the non-oil incubations (*p* = 0.002). This reduction in available P could be explained by the increased microbial P in the oil-treated systems, since respiration rates were higher in oil-treated systems.

Soil Contaminant Properties: Pb

All treatment options reduced soil Pb below the USEPA soil screening level of 400 mg kg⁻¹. Across all soil-capping options, estimated total soil Pb using Mehlich-3 Pb was 8 ± 1 mg kg⁻¹. The incorporation treatment resulted in 9 ± 2 mg Pb kg⁻¹. Compost mixed into the soil resulted in 196 ± 33 mg Pb kg⁻¹. Of the three tested management options, soil capping and incorporating soil blend components reduced soil Pb hazards the greatest amount. The compost addition only resulted in soils with estimated total soil Pb concentrations above the suggested 150-mg Pb kg⁻¹ screening level for bare residential soils (Henry et al., 2015). One potential explanation for Pb values being reduced further than suggested by either volumetric or mass mixing ratios could be due to pH changes within the Mehlich-3 extracting solution. If treated soils increase the Mehlich-3 solution pH, the solution could extract less Pb. A second explanation is that the added compost and associated compost P could have reduced soil Pb bioaccessibility. There is a need to identify the range of soil pH and soil Pb values for which rapid screening using common soil tests can be used. Soil blend components must also be evaluated for soil Pb concentrations, since Compost A and Compost B had different Pb levels, 38 and <10 mg kg⁻¹, respectively (Supplemental Table S1).

PAH Extraction Quality Control

Recoveries for BaP blank spikes were between 82 and 122% across tested concentrations from 5 to 0.005 mg L⁻¹. Photodiode array results were able to detect these blank spikes at

0.01 mg BaP L⁻¹ with 84 to 97% accuracy. These 0.01-mg BaP L⁻¹ recoveries demonstrated quality control acceptance criteria as outlined by USEPA 8100 (USEPA, 1986). Sand spiked with 10 µg mL⁻¹ of the 15 PAHs resulted in 39% recovery for acenaphthene, 80% for diben(a,h)perylene, and 129% for anthracene. All recoveries for the other 12 evaluated PAHs were between 88 and 122%. Spike recovery for BaP in the 15-PAH mix was 98%.

Soil Contaminant Properties: PAHs

Unamended urban soil samples collected from five locations in the yard were analyzed by ALS Environmental (Table 4). Sample locations 1 and 2 were previously located beneath a building, and the surface soil collected likely represented fill soil used postdemolition. Samples 3, 4, and 5 were collected from the historic yard area. The soil collected for use in the treatment experiment was collected from this historic yard area. Calculated TEFs ranged from 0.77 to 7.44 mg kg⁻¹, and all BaP concentrations were above the USEPA screening level of 0.016 mg kg⁻¹.

These same soil samples were extracted using the QuEChERS method (Table 5). Benzo(a)pyrene demonstrated similar extraction efficiencies across all five samples, with an average extraction efficiency of 0.62 ± 0.03. Most PAHs detected across all urban soil samples resulted in less-reproducible extraction ratios at the lower PAH concentrations seen in urban soil samples 1 and 2. Benzo(a)anthracene had similar extraction efficiencies (0.61 ± 0.02) to BaP.

Estimated total BaP concentrations were compared across each management option (capping, compost, or incorporated) (Table 6). Paired *t* tests indicated no differences in BaP concentrations between oil and non-oil treatments (*p* = 0.256), Compost A and B treatments (*p* = 0.179), or Sediment A and B treatments (*p* = 0.46). Adding oil was not shown to increase BaP degradation when compared with the same treatments without oil. Results suggest soil capping and soil compost incorporation had similar effects on estimated total BaP (*p* = 0.50). Soil incorporation generated similar BaP results to surface capping, 0.99 ± 0.09 and 0.99 ± 0.41 mg kg⁻¹, respectively. Both values

Table 4. Polycyclic aromatic hydrocarbons (PAH) concentrations in five urban soil samples.†

PAH	Urban soil 1	Urban soil 2	Urban soil 3	Urban soil 4	Urban soil 5
	$\mu\text{g kg}^{-1}$				
Acenaphthene	ND‡	ND	ND	ND	ND
Acenaphthylene	ND	ND	ND	ND	ND
Anthracene	ND	ND	ND	1100	1600
Benzo(a)anthracene	430	270	2900	4300	5800
Benzo(a)pyrene	440	280	3000	4200	5500
Benzo(b)fluoranthene	570	400	4200	5700	7500
Benzo(k)fluoranthene	270	200	1500	2100	3000
Chrysene	460	310	3100	4400	5800
Dibenzo(a,h)anthracene	200	200	200	200	200
Indeno(1,2,3-cd)pyrene	280	200	1900	2600	3700
Benzo(g,h,i)perylene	290	ND	1900	2600	3500
Carbazole	ND	ND	ND	ND	ND
Dibenzofuran	ND	ND	ND	ND	ND
Fluoranthene	840	540	5500	8000	11,000
Fluorene	ND	ND	ND	ND	ND
Naphthalene	ND	ND	ND	ND	ND
Phenanthrene	540	270	3100	6000	6700
Pyrene	690	430	4600	6600	9200
Surrogate recovery: 2-fluorobiphenyl (%)	68.3	64.5	66.9	61	60
TEF, $\text{mg kg}^{-1}\text{\S}$	0.77	0.57	4.12	5.69	7.44

† Samples were analyzed by ALS Environmental (Cincinnati, OH) using USEPA 8270.

‡ ND, not detected; detection limits for the ND samples are $200 \mu\text{g kg}^{-1}$.

§ TEF, toxicity equivalency factors calculated by multiplying the USEPA priority PAH concentrations by the following factors: benzo(a)pyrene $\times 1$, benz(a)anthracene $\times 0.1$, benzo(b)fluoranthene $\times 0.1$, benzo(k)fluoranthene $\times 0.01$, chrysene $\times 0.001$, dibenz(a,h)anthracene $\times 1$, indeno(1,2,3-c,d)pyrene $\times 0.1$.

Table 5. Recovery fractions for five urban soil samples between acetonitrile extraction divided by certified analytical lab data.†

Polycyclic aromatic hydrocarbons	Urban soil 1‡	Urban soil 2	Urban soil 3	Urban soil 4	Urban soil 5	Average
Acenaphthene	§	§	§	§	§	§
Anthracene	§	§	§	0.22	§	§
Benzo(a)anthracene	0.56	0.67	0.54	0.60	0.65	0.61
Benzo(a)pyrene	0.66	0.71	0.53	0.54	0.65	0.62
Benzo(b)fluoranthene	1.14	1.21	0.76	0.75	0.87	0.95
Benzo(g,h,i)perylene	0.78	§	0.55	0.52	0.34	§
Benzo(k)fluoranthene	0.81	§	0.60	0.61	0.65	§
Chrysene	0.82	0.98	0.70	0.68	0.78	0.79
Dibenz(a,h)perylene	§	§	§	§	§	§
Fluoranthene	2.19	1.07	2.21	2.32	2.61	2.08
Fluorene	§	§	§	§	§	§
Indeno(1,2,3-cd)pyrene	1.40	1.53	0.98	0.94	0.68	1.11
Naphthalene	§	§	§	§	§	§
Phenanthrene	2.09	1.01	1.95	1.66	§	§
Pyrene	1.68	1.21	0.76	1.83	1.04	1.30

† Samples were analyzed by ALS Environmental (Cincinnati, OH) using USEPA 8270C.

‡ Each acetonitrile extraction sample was injected twice into the instrument and values averaged. Values reported for urban soil 1 are from the second injection only, due to an instrument error with the first injection.

§ Not computed since samples were not detected by at least one of the analytical laboratory or the acetonitrile extraction.

were below the $4.27 \pm 0.99 \text{ mg kg}^{-1}$ in the urban soil control. This estimate for total BaP concentration aligned with the average BaP concentration for the area where the bulk soil was collected, as indicated by the concentration of $4.23 \pm 0.72 \text{ mg BaP kg}^{-1}$ for urban soil samples 3 through 5 (Table 4).

The compost addition to the urban soil generated larger BaP variation compared with the other treatments, and this highlights the potential for uneven dilution effects when composts are added to contaminated surface soils. With soil capping, the

contaminated soil is more fully covered. Soil blend incorporation provided a greater volume of material for mixing and possibly diluting surface soil contaminants compared with adding compost alone.

Combined Soil Health and Contaminant Management Implications

Of the tested management options for this study's materials—(i) soil capping with sediment and compost, (ii) compost

Table 6. Estimated benzo(a)pyrene total concentrations using acetonitrile extraction on soil capping, compost only, and incorporation options.

Treatments	Volumetric mixing ratios	Benzo(a)pyrene† mg kg ⁻¹
Capping only		
All Sediment A/B combinations (n = 8)	50% sediment; 50% compost	0.99 ± 0.41
Compost only to urban soil		
All compost combinations (n = 4)	50% compost; 50% urban soil	3.57 ± 3.31
Incorporation		
All components combinations (n = 2)	33% compost; 33% urban soil; 33% sediment	0.99 ± 0.09
Source materials		
Urban soil		4.27 ± 0.99
Sediment A (expected high PAH‡) (n = 2)		1.08 ± 0.75
Sediment B (expect low PAH) (n = 2)		0.93 ± 0.49
Compost A (n = 2)		0.49 ± 0.01
Compost B (n = 2)		0.24 ± 0.00

† Total benzo(a)pyrene calculated by dividing acetonitrile extractable results by the 0.62 factor identified in Table 5.

‡ PAH, polycyclic aromatic hydrocarbons.

addition, and (iii) incorporating sediment and compost into the urban soil—only option (iii) reduced soil contaminant exposure and maintained soil health, as measured by reduced Pb and PAH contaminant concentrations, and by maintaining soil organic C values and soil aggregate stability. Oil addition was not shown to increase soil BaP degradation in these field-contaminated soils using approximately 6.4 to 8.5% oil addition on an oven-dry soil mass basis. Blend incorporation generated similar soil health data to the control urban soil, reduced Mehlich-3-extractable Pb below 150 mg kg⁻¹, and did not increase estimated total BaP concentration above the capping-only option. The incorporation management option added sand and compost to the soil, and the sand would allow for longer-term surface soil Pb and PAH dilution as compost would degrade over time. The incorporation option BaP concentration was 0.99 ± 0.09 mg kg⁻¹, and this value was above the USEPA soil screening level of 0.016 mg kg⁻¹ and below the Ohio VAP soil screening level of 1.2 mg BaP kg⁻¹. This finding raises questions about how regulators may apply soil screening criteria to soil blends demonstrating reductions below site-specific PAH background data when levels are between existing screening levels. Regulatory soil screening levels and site-specific measurements should be compatible to promote sound management of soil resources.

Soil blends may be suitable if bioavailability-based standards are applied or if different soil hazards are evaluated for soil blends. As demonstrated by Attanayake et al. (2015), soil PAH bioavailability to plants may result in concentrations below levels of concern in the vegetables. Further, Ruby et al. (2016) identified soil PAH bioavailability being below an assumed 100% bioavailability due to soil and contaminant properties. The methods used to evaluate soil blend suitability for remediating urban soils remains an open area of research to resolve these situations, in which a blend reduces the initial soil PAH concentration but remains above soil screening levels.

Other metrics used to evaluate soil blend efficacy could include reduced soil dust hazards caused by robust groundcover growth. In combination with quantifying reduced dust hazards, researchers can also characterize how much soil Pb or PAHs are taken up into the groundcover. This metric may be of particular interest if the groundcover includes edible plants. The rate of contaminant uptake depends on soil contaminant concentrations, soil properties, and the plant of interest. Plants grown in soils and composts containing Pb and PAHs might not accumulate contaminants above regulatory levels of concern, although variation can occur among plant types (Attanayake et al., 2015). Phytoavailability of Pb is a concern for root vegetables, such as radish (*Raphanus sativus* L.), potatoes (*Solanum tuberosum* L., *Ipomoea batatas* L.), and carrots (*Daucus carota* L. var. *sativus* Hoffm.), and leafy green vegetables, such as lettuce (*Lactuca sativa* L.), grown in soils with elevated soil Pb. In a study conducted on three soils with increasing levels of contamination, the Pb uptake for these plants of concern was the highest in the most contaminated soil. The most contaminated soil had a mean of approximately 1000 mg Pb kg⁻¹, although the sample values ranged up to 11,000 mg Pb kg⁻¹ (Samsøe-Petersen et al., 2002).

Phytoavailability of BaP is a concern for root vegetables and leafy green vegetables grown in highly contaminated soils. In the same study, these crops were grown in soils containing a mean of 15 mg BaP kg⁻¹ of soil (range: 1.4–160 mg BaP kg⁻¹ soil) (Samsøe-Petersen et al., 2002). Carrots and lettuce grown in soils with lower BaP levels (e.g., <1.0 mg BaP kg⁻¹) did not accumulate large amounts of BaP (Wild and Jones, 1992; Samsøe-Petersen et al., 2002).

While plant uptake of Pb and BaP can occur in these situations, more Pb contamination of foods occurs from soil particle splash and transfer onto the food (McBride et al., 2013, 2014; Attanayake et al., 2014). Thoroughly washing vegetables removes the soil particles and reduces exposure to soil Pb (Attanayake et al., 2014). Washing might not be sufficient for carrots grown on historically lead arsenate-treated soils that took up Pb into plant tissues and not just on the peel surface (Codling et al., 2015). If someone is in a situation in which plant uptake of Pb or BaP is of a concern, they could grow crops other than leafy greens and root vegetables. However, there are contaminated soils in which gardens should not be grown. Some of the soils included in the Samsøe-Petersen et al. (2002) study would present much larger health hazards from direct soil ingestion than from plant uptake. No one should be gardening or working on a soil in an urban area with 11,000 mg Pb kg⁻¹ of soil.

Soil contaminant properties affect how well soil blends reduce or remediate the soil hazard. As an element, Pb cannot be degraded. Soil blends could potentially alter soil solution chemistry to form less-soluble Pb minerals in situ using P amendments, such as monoammonium phosphate, diammonium phosphate, or triple super phosphate, although the efficacy of this treatment approach is mediated by soil and contaminant properties (Scheckel et al., 2013; Henry et al., 2015). The soil blend could serve a soil capping function and cover surface soil Pb. Incorporated materials could dilute the soil Pb. If the diluting agent is only compost, however, the compost can degrade over time and the surface soil Pb concentration would theoretically return to precompost-addition levels. Except for complete soil removal and replacement with tested low-Pb materials, using soil blends on Pb-contaminated soils could still result in Pb concentrations above various soil screening levels.

Soil PAHs can be capped, diluted, or degraded by soil blends. This degradation potential is mediated by the PAH contaminant form and soil properties (Ruby et al., 2016). The lack of increased PAH degradation for the soils in the current study fit well within existing PAH degradation literature. More research is needed to evaluate urban soil PAH types and identify if petrogenic or pyrogenic forms predominate. Soil blends could be tailored to specific contaminant types and whether or not degradation might be a goal, particularly for petrogenic PAHs. For example, aerobic remediation works well on petrogenic (i.e., creosote-contaminated) PAH-contaminated sites (Keck et al., 1989; Lladó et al., 2013; García-Delgado et al., 2015), but not as well on pyrogenic (i.e., coal, lampblack, char) PAH-contaminated sites (Weissenfels et al., 1992; Erickson et al., 1993; Stroo et al., 2000; Ghosh et al., 2003; Achten et al., 2011; Barnier et al., 2014) due to differences in PAH bioavailability. An excellent example of this difference was demonstrated by Weissenfels et al. (1992). Soil incubations containing petrogenic PAHs degraded, but soils with pyrogenic PAHs did not. The pyrogenic PAHs were extracted using toluene, this extract was placed back in the same soil, and the added PAHs degraded (Weissenfels et al., 1992). Soil blends could include surfactants to potentially increase PAH solubility (Yap et al., 2010; Lladó et al., 2013). Unintended effects can occur, as surfactants can disrupt microbial cell walls, cause excessive micelle formation that decreases availability, or become microbial substrates and divert degradation activity from the PAHs (Juhasz and Naidu, 2000).

Multiple studies indicate that PAH concentrations can remain elevated in the soil above regulatory screening levels after several years. Soil from a manufactured gas plant, likely pyrogenic PAHs, was composted for 3 yr and then placed in a biopile for 14 mo. Polycyclic aromatic hydrocarbon levels decreased from 1400 to 50 mg kg⁻¹, but this concentration remained above the 4-mg PAH kg⁻¹ standard applied to the soil (Reichenberg et al., 2010). Benzo(a)pyrene levels remained at ~3 mg kg⁻¹ after 1 yr of treatment using composted biosolids, noncomposted biosolids, leaf compost, and mushroom compost (Attanayake et al., 2015), and this concentration was above the USEPA BaP soil screening level. Materials land farmed beginning in the mid-1990s with PAH concentrations between 52 and 550 mg kg⁻¹ had levels of 2 to 25 mg PAH kg⁻¹ in 2004 (Harmsen et al., 2007). These results demonstrated that PAH levels can remain elevated years after land farming begins due to potentially limiting oxygen, insufficient microbial populations, and reduced contaminant bioavailability (Harmsen et al., 2007).

Future Uses of Dredged Materials for Urban Soil Restoration

Dredged sediments can be reused as a soil material in a number of contexts, including habitat restoration, crop production, and general upland placement. Sediment properties vary according to collection location and the associated mineralogy in a given area (Brown et al., 1980; Gupta et al., 1980; Combs et al., 1982, 1983). If tested dredged material meets the necessary environmental standards, then it can be beneficially applied and the application's impacts can be evaluated (Darmody and Marlin, 2002; Ebbs et al., 2006; Baniulyte et al., 2009; Diaz et al., 2010). Questions remain about ensuring that suitable dredged sediment screening

protocols are developed to identify when materials can be reused (Koropchak et al., 2016), and if sediments are used in soil blends, there must be adequate screening criteria for the blends.

Future Use of QuEChERS PAH Extraction

Reichenberg et al. (2010) recommended conducting a pollutant accessibility assessment before remediation efforts begin. These tests can include PAH bioavailability and can be conducted using a range of methods, including using Tenax beads for desorption studies and hydroxyl- β -cyclodextrin extractions for bioaccessibility estimates (Cornelissen et al., 1998; Reid et al., 2000; Stroo et al., 2000; Semple et al., 2003; Juhasz et al., 2014). Within the soil used in the current study, the QuEChERS-extractable BaP could estimate total BaP, but more data are needed before this method is suggested as a soil PAH screening tool.

Conclusions

Urban soil management must emphasize reducing soil contaminants and promoting soil physical, chemical, and biological properties that allow soils to function as critical ecosystem components. Associated soil screening criteria should be developed to allow soil blend evaluation across all these soil properties, in addition to ensuring soil blends do not pose soil contaminant hazards. Of the three treatment options studied, incorporating the compost and sediments with the soil accomplished both these objectives. This option maintained or increased soil chemical and biological properties, including aggregate stability and soil organic matter, while reducing estimated total soil Pb to 15 mg kg⁻¹ and BaP to 0.99 \pm 0.09 mg kg⁻¹. Oil addition did not increase BaP degradation when using 6.4 to 8.5% oil addition on a dry mass basis for field-contaminated urban soils. Oil treatments increased respiration values to 1.4 \pm 0.7 mg CO₂ g⁻¹ higher than the non-oil treatments ($p = 0.001$). Future studies should evaluate how incorporating soil blends in different soil types with a range of contaminants may offer a suitable long-term management option for widespread urban soil contaminants.

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