Journal of Environmental Management 214 (2018) 354–361

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Sediment exchange to mitigate pollutant exposure in urban soil

Daniel Walsh [a, b, *], Katherine Glass [b], Samantha Morris [b], Horace Zhang [b], Isabel McRae [b], Noel Anderson [b], Alysha Alfieri [b], Sara Perl Egendorf [c], Shana Holberton [b], Shahandeh Owrang [b], Zhongqi Cheng [c]

[a] *Columbia University, Lamont Doherty Earth Observatory, USA*
[b] *New York City Office of Environmental Remediation, USA*
[c] *Brooklyn College of the City University of New York, USA*

ARTICLE INFO

Article history:
Received 5 March 2017
Received in revised form
28 February 2018
Accepted 3 March 2018

ABSTRACT

Urban soil is an ongoing source for lead (Pb) and other pollutant exposure. Sources of clean soil that are locally-available, abundant and inexpensive are needed to place a protective cover layer over degraded urban soil to eliminate direct and indirect pollutant exposures. This study evaluates a novel sediment exchange program recently established in New York City (NYC Clean Soil Bank, CSB) and found that direct exchange of surplus sediment extracted from urban construction projects satisfies these criteria. The CSB has high total yield with 4.2×10^5 t of sediment exchanged in five years. Average annual yield (8.5×10^4 t yr^{-1}) would be sufficient to place a 15-cm (6-in.) sediment cover layer over 3.2×10^5 m^2 (80 acres) of impacted urban soil or 1380 community gardens. In a case study of sediment exchange to mitigate community garden soil contamination, Pb content in sediment ranged from 2 to 5 mg kg^{-1}. This sediment would reduce surface Pb concentrations more than 98% if it was used to encapsulate soil with Pb content exceeding USEPA residential soil standards (400 mg kg^{-1}). The maximum observed sediment Pb content is a factor of 42 and 71 lower than median surface soil and garden soil in NYC, respectively. All costs (transportation, chemical testing, etc.) in the CSB are paid by the donor indicating that urban sediment exchange could be an ultra-low-cost source for urban soil mitigation. Urban-scale sediment exchange has advantages over existing national- or provincial-scale sediment exchanges because it can retain and upcycle local sediment resources to attain their highest and best use (e.g. lowering pollutant exposure), achieve circular urban materials metabolism, improve livability and maximize urban sustainability.

1. Introduction

Surface soil in urban areas is a significant sink and reservoir for anthropogenic pollutants (Laidlaw et al., 2017; Mielke et al., 2016). Pollutant sources are well documented and include atmospheric deposition of discharges from products with lead (Pb) additives, such as gasoline and leaded paint (Mielke and Reagan, 1998; Mielke et al., 2013; Filippelli et al., 2005), combustion of fossil fuels (Chillrud et al., 1999; Louchouarn et al., 2007), and waste incineration (Walsh et al., 2001); discharge from industrial and commercial operations (Callendar and Rice, 2000; Alloway, 2013); and historical placement of anthropogenic fill material to raise and level urban land (Meuser, 2010; Walsh and LeFleur, 1995). Shallow urban soils can be degraded by Pb, other metals and polycyclic aromatic hydrocarbons (PAH; De Kimpe et al., 2000; Krauss and Wilcke, 2003; Azzolina et al., 2016; Mielke et al., 1983; Datko-Williams et al., 2014; Burt et al., 2014; Cheng et al., 2015) and can contribute to increased public health risks, such as increased levels of Pb in the blood of children (Mielke and Reagan, 1998; Laidlaw et al., 2016). These risks can disproportionately affect people in low-income neighborhoods, indicating the environmental justice aspects of this issue (McClintock, 2015).

Many urban communities have established communal gardens on vacant lots and available open spaces (Chan et al., 2015). Pollutants in garden soil have the potential to be incorporated into plant tissue or may be adhered to the surface of harvested vegetables, posing health risk through ingestion (Intawongse and Dean, 2006; Finster et al., 2004; McBride et al., 2014). Other mechanisms

* Corresponding author. 67 Viola Road, Suffern, NY 10901, USA.
E-mail address: dcw43@columbia.edu (D. Walsh).

https://doi.org/10.1016/j.jenvman.2018.03.013
0301-4797/Published by Elsevier Ltd.

of exposure include incidental ingestion and inhalation of soils by gardeners and children that work and play on exposed soil in and around these gardens (Clark et al., 2008; Ljung et al., 2006), tracking into homes on shoes and clothing (Sheldrake and Stifleman, 2003) and resuspension of soil and dust particles (Caravanos et al., 2006; Zahran et al., 2013; Clark et al., 2008). Like other urban soils, community gardens can have elevated levels of pollutants that can exceed USEPA residential soil standards (Cheng et al., 2015; Marquez-Bravo et al., 2015; Spliethoff et al., 2016; Clark et al., 2008; Federal Register, 2001). Table 1 compares literature reports of the content of trace metals and PAH in surface soil (RETEC, 2007) and garden soil (Cheng et al., 2015) in New York City (NYC), natural sediment (Rose et al., 1979) and USEPA residential soil standards (Federal Register, 2001).

Remediation to address high Pb contamination in soil from large point sources, such as smelters and mines, has involved removal of contaminated soil prior to placement of a clean soil cover (Laidlaw et al., 2017). These interventions have resulted in significant reduction of Pb content in soil, house dust, and children's blood (Lanphear et al., 2003 [Utah]; Schoof et al., 2016 [Montana]; Sheldrake and Stifelman, 2003 [Idaho]). Soil removal actions are extremely expensive and implementing them for soil pollution interventions over large areas in urban settings is cost prohibitive (Laidlaw et al., 2017; Clark et al., 2008). The cost of soil removal followed by soil cover was reported to be 18 times greater than soil cover alone (Mielke et al., 2016). Remediation for non-point-source Pb in urban soil typically involves placement of clean soil cover without prior soil removal (encapsulation). Encapsulation is a primary pollution prevention approach that acts by transforming surface soil environments from Pb-contaminated to Pb-safe to correct hazards before exposure can occur (Mielke et al., 2007, 2011a). Significant reductions of soil Pb content and exposures at various scales have been reported for encapsulation interventions, including individual homes, neighborhoods, villages and cities (Laidlaw et al., 2017; Mielke et al., 2011a; Ericson, 2014). Encapsulation typically involves placement of a 15-cm (6 in.) clean soil cover layer and has been used in New Orleans (Mielke et al., 2011a), Vietnam (Ericson, 2014) and Nigeria (Tirima et al., 2016). The challenge for urban soil encapsulation programs is obtaining locally-available, clean soil in sufficient quantity to cover large areas of degraded soils (Laidlaw et al., 2017). High cost of clean soil is also an important factor that could limit the rate of encapsulation of urban soil. Assuming a cost of \$115 USD/m^3 $\pm$19% for purchase, delivery and placement of clean soil (Tables SI-1, supplemental information), it would cost approximately \$4000 USD to place a 15-cm clean soil layer on top of a single community garden with the area of a typical urban residential lot (230 m^2).

No studies have reported use of urban-derived sources of clean soil for soil encapsulation. Large amounts of clean soil are available in the outskirts of cities (Laidlaw et al., 2017; Mielke et al., 2011a, 2013), but ongoing programs that provide soil from these sources for urban soil encapsulation have not been reported. Exchange programs that transfer surplus clean sediment directly between construction projects to promote recycling have developed in several countries, including South Korea (Moon et al., 2007), France (Blanc et al., 2012), Australia (Choi et al., 2017), England and Wales (CL:AIRE, 2011) and Ontario, Canada (RCCAO, 2012). These programs serve public and private construction projects and are typically run at the national or provincial scale using online matching of sediment generators and recipients, and self-implementation according to government regulations or a code of practice. We found no reports of a sediment exchange run by a city to retain and reuse surplus clean sediment.

Recent materials management research has emphasized the retention and reuse of surplus sediment and other clean materials generated during construction in cities to achieve circular material metabolism (Huang and Hsu, 2003; Huang et al., 2010). The fate of urban material flows is an important indicator of urban

Table 1
A summary of literature reports showing the range and median (parenthesis) content of metals and PAH in NYC shallow soil (0–5 cm; RETEC, 2007) and NYC garden soil (Cheng et al., 2015). Data are compared to USEPA residential soil standards (RSS; Federal Register, 2001) and natural sediments not impacted by anthropogenic pollutants (Rose et al., 1979). Concentration of common urban pollutants in NYC surface soil and garden soil can exceed natural sediment content by several orders of magnitude. All values are in mg kg^{-1}. ND signifies not detected at the method detection limit. NS signifies no standard exists for this parameter.

	NYC Shallow Soil[a]	NYC Garden Soil[b]	Natural Sediment[c]	RSS
Arsenic	4–28 (12)	0.90–76 (10)	(8)	16
Chromium	15–196 (22)	4–262 (49)	(6)	180
Copper	23–222 (45)	5–1,286 (77)	(15)	270
Lead	48–3,160 (211)	3–8,912 (355)	(17)	400
Mercury	0.14–3.30 (0.52)		(0.06)	0.81
Nickel	10–48 (22)	2–333 (28)	(17)	310
Zinc	64–2,080 (164)	35–2,352 (248)	(36)	10,000
Acenaphthene	0.004–0.63 (0.06)			100
Acenaphthylene	0.01–0.14 (0.01)			100
Anthracene	0.01–1.10 (0.13)			100
Benzo(a)anthracene	0.07–2.10 (0.45)			1
Benzo(a)pyrene	0.07–2.00 (0.46)			1
Benzo(b)fluoranthene	0.07–1.80 (0.55)			1
Benzo(g,h,i)perylene	0.14–1.50 (0.34)			100
Benzo(k)fluoranthene	0.06–2.00 (0.48)			3.9
Chrysene	0.82–2.400 (0.55)			3.9
Dibenzo(a,h)anthracene	0.03–0.48 (0.08)			0.33
Fluoranthene	0.12–5.20 (1.10)			100
Fluorene	0.003–0.60 (0.05)			100
Indeno(1,2,3-cd)pyrene	0.05–1.50 (0.35)			0.5
Naphthalene	0.002–0.21 (0.02)			100
Phenanthrene	0.06–4.40 (0.61)			100
Pyrene	0.11–4.70 (0.87)			100

[a] n = 27 shallow soil samples.
[b] n = 1,652 garden soil samples for Pb and 475 garden soil samples for other metals.
[c] Median for natural sediment.