MOSS & SOIL MONITORING TO MEASURE FOREST HEALTH IMPLICATIONS IN SEATTLE, WASHINGTON

Green Seattle Partnership + Seattle Parks & Recreation

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TRACKING URBAN POLLUTION USING MOSS AND SOIL-BASED MEASUREMENTS IN SEATTLE, WA

There is a long history of using moss as an inexpensive screening tool to assess areas of metal pollution from the atmosphere. Our objectives with this study were to identify “hotspots” of heavy metal pollution in both moss tissue samples and soil samples collected across 25 priority restoration sites for Green Seattle Partnership and Seattle Parks & Recreation. We measured 20 elements in moss tissue and soil samples collected across Seattle, WA in January 2018 to determine the extent of threat pollution is having on urban forest health. Summary statistics, dot maps, histograms, Pearson correlation tests, and Principal Component Analysis were used to describe the distribution of each element in moss and soil samples across the sampling locations. We identified several areas to focus restoration activities to reduce heavy metal levels using a combination of planting and soil amendment strategies.

Keywords: Heavy metals, moss, soil, mapping, urban forestry.

In 2005, Green Seattle Partnership (GSP) set out to restore 2,500 acres of Seattle's forests by 2025. With over 1,300 acres in restoration in over 136 parks, GSP is well on the way to sustaining and maintaining healthy urban forest conditions across the city. In order to continue to advance ecological restoration, GSP utilizes the best available science to help guide best management practices and restoration activities.

Current forecasts for population growth in the Puget Sound Region (PSR) is expected to reach 4.9 million by 2040, which will in turn increase demand for travel throughout the region by 25% (Puget Sound Regional Council, 2014). As evidence of this increase, Seattle highways and roads were recently ranked the 9th most congested urban areas in the United States (Cookson & Pishue, 2017). This region-wide expansion in the transportation sector has introduced a set of atmospheric pollutants to urban traffic corridors throughout Seattle.

Brake and tire attrition, as well as lubricant degradation, produce high rates of metal deposition in highly congested areas (Garg et al., 2000; Apeagyei et al., 2011; Hulskotte et al., 2014). These transportation pollutants as well as inputs from residential and commercial construction projects have the potential to negatively impact ecosystem health by altering moss and soil communities (Davies et al., 2007; Aničić et al., 2009; Zvereva and Kozlov, 2011).

The question remains as to how Seattle's urban forests will tolerate and adapt to changes in urban pollution throughout the area.

WHY USE MOSS TO MEASURE POLLUTION?

The literature documents a long history of using moss as bioindicators of air quality and atmospheric pollution (Ruhling & Tyler, 1968; Reimann et al., 2001; Aboal et al., 2010; Ćujić et al, 2014; Donovan et al., 2016). Unlike vascular plants, moss lack roots and absorbs most nutrients from the atmospheric (Bates, 1992). Moss leaves lack a protective epidermis and demonstrates ion exchange properties, all of which allows for the absorption of water, organic compounds and inorganic ions that are deposited on their surfaces (Gjengedal & Steinnes, 1990; Aboal et al., 2011; Gonzalez & Pokrovsky, 2013).

The time period represented for pollutant accumulation in moss tissue consistently ranges from several months to a maximum of three years. As there is little recycling of metals from senescent tissue (Brown & Bates, 1990), the concentration of metals in the upper two-thirds of moss shoots can be used to infer metal deposition over a three year or less time period (Bargagli, et al., 2002; Schintu et al., 2005; Gatziolis et al., 2016).

In 2013, the United States Forest Service (USFS) analyzed Orthotrichum lyellii moss samples to assess the spatial distribution of atmospheric pollution across Portland, Oregon. Researchers observed "hotspots' of cadmium (Cd) and arsenic (As) in sampling locations near two stained-glass manufacturers (Donovan et al., 2016). Results from this study prompted the Oregon Department of Environmental Quality to place instrumental air monitor near the stained-glass manufacturers for long-term monitoring efforts.

Most recently, heavy metal pollution across Western Washington was assessed in 2016 and 2017 using Isothecium stoloniferum and Kindbergia praelonga (Bidwell, 2017). This study analyzed moss samples across an urban-to-wildland gradient for Cd, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, Sr, Ti, and Zn. Elevated concentrations of all of these elements were found in samples collected in Seattle, followed by sites along I-90, with the lowest levels were observed on the Olympic Peninsula. This suggests that the influence of urbanization and vehicular pollution sources can be observed using moss elemental analysis.

SOIL BASICS

Plants can only take up nutrients that are in solution (i.e. dissolved in soil water). Most soil nutrients are not in solution; they are tied up in soil mineral and organic matter. These nutrients become available to plants only after they are converted to soluble forms and dissolve into the soil solution.

Nitrogen (N) is an essential plant nutrient responsible for many functions in plants, including photosynthesis and tissue growth (Spargo et al., 2012). The bulk of soil nitrogen is in organic compounds such as humus and proteins, which is largely unavailable to plants. Two forms available to plants are nitrate (NO3-) and ammonium (NH4+). These forms of N fluctuate constantly in soils and do not remain stable even in one growing season. Nitrates are easily leached from soils when they exist in areas that experience high rainfall (Brady and Weil, 2008). Both NH4+ and NO3- taken up by plants are eventually converted to organic forms of N in plant tissue, which can be returned to the soil as they slowly decompose. Measuring extractable NH4 and NO3 in January gives a baseline understanding on available N levels during the rainy season in Seattle's urban forests.

Understanding natural background levels of metals in urban soil environments is important for clean-up and forest restoration strategies. The Model Toxics Control Act (Ch 173-340-200 WAC) defines "natural background as the concentration of hazardous substance consistently present in the environment which has not been influenced by localized human activities." Washington State's Department of Ecology has defined natural background levels for the PSR using the 90th percentile value for Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn (San Juan, 1994).

Metals in their various forms can exist in the pore-water as charged species, as soluble complexes, or precipitate out of solution. Measuring mineral soils samples for a suite of metals has the potential to help guide plant strategies across GSP restoration sites.

There is a long history of using moss as an inexpensive screening tool to assess areas of heavy metal pollutants from the atmosphere. Our objectives with this study was to identify “hotspots” of heavy metal pollution in both moss tissue samples and soil samples collected across 25 restoration sites for Green Seattle Partnership (GSP) and Seattle Parks & Recreation.

Sampling locations were selected taking into account areas where moss was abundant, target forest type, and the location of the site with respect to elevation and aspect. Figure 1 indicates sampling locations with target ecosystem types identified as well as the corresponding GSP restoration phase. The phases are as follows: 0 = no active restoration; 1 = initial invasive plant removal; 2 = native plant installation; 3 = native plant establishment and continued weeding; and 4 = long-term stewardship and maintenance.

We collected moss and soil samples between January 9th- 11th, 2018. We sampled Orthotrichum lyellii Hook. & Taylor, a moss that grows abundantly on the trunks and branches of hardwood trees across the Pacific Northwest. We chose this species because of its wide distribution across the city and it has been used in previous biomonitoring studies in the region (Gatziolis et al., 2016; Donavan et al., 2016). Roughly 5-7g (dry weight) of moss was collected from each sampling location.

Five composite soil samples (0–30 cm) were collected from each of the 25 sampling locations. The soil was thoroughly homogenized and passed through a 2 mm sieve. Soil bulk density measurements were collected at the same time using a bulk density core that was pressed into the soil. Bulk density gives an understanding of the level of compaction across sampling locations and how it might impact nutrient availability via root growth restriction.

Map of Green Seattle Partnership Sampling Locations

Dot map indicates sample locations with corresponding target ecosystem type. Samples are color-coded as Pink, orange, green, and blue based on the 4 target ecosystem types for this study. The different shapes represent 5 GSP restoration phases.

Conifer Broadleaf Evergreen Mixed Forest:
Northacres Park

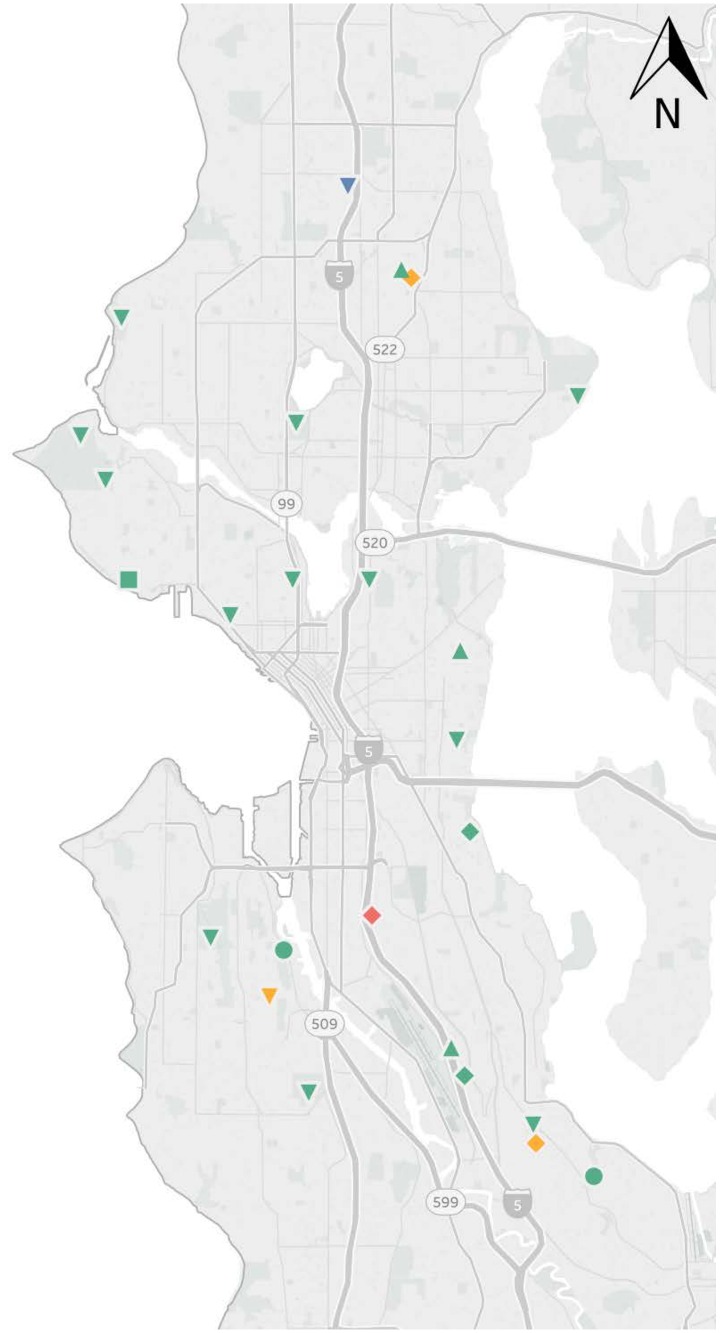
Dry-Mesic Conifer and Conifer Deciduous Forest:
Camp Long, Discovery Park 1/2, East Duwamish Greenbelt 1/2, Frink Park, Golden Gardens, Harrison Ridge Greenbelt, Kingfisher Natural Area #1, Kinnear Park, Kubota Gardens Natural Area 1, Lakeridge Park, Magnolia Park, Magnuson South Park, Mt Baker Park, Northeast Queen Anne Greenbelt, St. Mark's Greenbelt, Westcrest Park, West Duwamish Greenbelt 1, Woodland Park

Mesic-Moist Conifer and Conifer Deciduous Mixed Forest:
Kingfisher Natural Area 2, Kubota Gardens Natural Area 2, West Duwamish Greenbelt 2

Riparian Forest and Shrubland:
Maplewood Playfield

GSP restoration phases:

- ■ 0
- ▲ 1
- ◆ 2
- ▼ 3
- ● 4



Prior to analysis, all debris and necrotic tissue were removed with sterilized plastic forceps from the base of moss samples keeping only the upper two-thirds of the shoots (Gatziolis et al., 2016). Elemental analysis for moss samples was carried out using the acid digestion method described in Donovan et al. (2016). Moss digests were analyzed for a suite of elements (Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Ni, P, Pb, Si, Sr, Ti, Zn) using inductively coupled plasma optical emission spectrometry (ICP-OES).

Soil samples were thoroughly homogenized and passed through a 2 mm sieve. Soil samples (5 g) were weighed out, shaken with 30 ml of 1.0 M KCl, filtered and analyzed for extractable nitrate (NO3-N) and ammonium (NH4-N) using a flow-injection auto-analyzer (FIA). Elemental analysis for soil samples was carried out using the EPA 3050b method (acid digestion for sediments, sludges, and soil). Similar to the elemental analysis of the moss samples, soil digests were analyzed for the same suite of elements using ICP-OES. Table 1 shows element names, units, and classification.

All moss and soil samples were processed by the Analytical Service Laboratory at the University of Washington’s School of Environmental & Forest Sciences.

**TABLE 1:
NAMES, SYMBOLS &
CLASSIFICATIONS OF ELEMENTS
ANALYZED**

Soil Variables	Symbol (unit)	Class
Bulk Density	g/cm^3	Physical characteristic
Ammonium	NH_4^-N (kg/ha)	Plant-essential macronutrients
Nitrate	NO_3^-N (kg/ha)	
Soil and Moss Variables	**Symbol (unit)**	**Class**
Phosphorus	P (mg/kg)	Plant-essential macronutrients
Potassium	K (mg/kg)	
Calcium	Ca (mg/kg)	Plant-essential secondary nutrients
Magnesium	Mg (mg/kg)	
Copper	Cu (mg/kg)	Plane-essential micronutrients
Iron	Fe (mg/kg)	
Manganese	Mn (mg/kg)	
Molybdenum	Mo (mg/kg)	
Nickel	Ni (mg/kg)	
Zinc	Zn (mg/kg)	
Aluminum	Al (mg/kg)	Soil minteral elements
Barium	Ba (mg/kg)	
Silicon	Si (mg/kg)	
Strontium	Sr (mg/kg)	
Titanium	Ti (mg/kg)	
Arsenic	As (mg/kg)	Environmentally important trace elements
Cadmiums	Cr (mg/kg)	
Cobalt	Co (mg/kg)	
Chromium	Cd (mg/kg)	
Lead	Pb (mg/kg)	

Descriptive statistics (minimum, maximum, mean, median, standard deviation, and Fisher-Pearson Skewness coefficient) were calculated for each element for both moss and soil samples. A Pearson product-moment correlation test was used to identify shared or common sources across elements of interest.

Principal component analysis (PCA) was selected as the appropriate ordination method to highlight the relationships between element concentrations for both the moss and soil datasets. PCA allows for the extracting of major patterns among variables into a 2D space. 20 moss elemental parameters (Al, As, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Ni, P, Pb, Si, Sr, Ti, Zn) were introduced as the analysis variables in the first PCA; and 22 soil elements (suite of elements listed in PCA1 plus extractable $NH4+$ and $NO3-$) were introduced as the analysis variables in the second PCA. The significance of each principal component (PC) was evaluated and the loadings of variables to each PC was examined by converting eigenvector coefficients to structure correlations.

Enrichment Factor (EF) analysis was used to differentiate in moss samples elements mainly originating from anthropogenic sources or natural origin. EF was calculated by assuming that most of the aluminum in the moss tissue was of terrestrial origin and expressing the concentration of element X in the moss tissue compared to the concentration of element X in the soil as ratios to the corresponding Al concentrations, according to the following formula:

$$EF = \frac{([X\ moss]/[Al\ moss])}{([X\ soil]/[Al\ soil])}$$

According to the degree of enrichment the elements may be grouped as follows: highly enriched ($EF > 100$); intermediately enriched ($10 < EF < 100$); slightly enriched ($EF < 10$); and no enrichment ($EF < 1$) (Berg et al., 1994; Wang et al., 2005). If the EF approaches unity ($EF < 1$), crustal material is likely to be the predominant source of the element; if $EF > 1$, the element contains a fraction contributed by non-crustal sources.

A summary table of the descriptive statistics for moss and soil samples, including mean, median, minimum, maximum concentrations of all the elements, can be found in tables 2 & 3 (respectively). Fisher-Pearson skewness coefficient was calculated to identify elements with extremely high concentrations (Shepard, 1968). Moss samples were relatively free of exceptionally high concentrations, resulting in smaller skewness coefficients.

Dot maps for each of the 20 elements were generated and sampling locations were color-coded by concentrations measured in the moss tissue, using a green-yellow-red color ramp to indicate low-to-high concentrations. Histograms of element concentrations were also color-coded. The maps for all the elements can be found in fig. 2a-2s.

Dot maps were also created for top 6 (As, Cd, Co, Cr, Ni, Pb) and top 10 elements (Al, As, Cd, Co, Cr, Cu, Fe, Mo, Ni, Pb) most toxic elements in the moss dataset (Gatziolis et al., 2016). The dot maps, for both the top 6 and 10 toxins, show where moss concentrations were in the top six highest (fig. 3 & 4, respectively). Locations were ranked with high concentrations of multiple elements of concern to prioritize 'hotspots' for further investigation. From the moss concentration dot maps, we can identify several air pollution 'hotspot' sites including: Kingfisher Natural Area #2 - 98th St slope, East Duwamish Greenbelt 1 and 2 (Chicago St and Cloverdale St, respectively), and Westcrest Park - 4th Ave SW.

Correlations between element concentrations in moss samples are show in table 4. Correlations higher than 0.5 are shaded in gray; shading becomes progressively darker as the strength of the correlation increases. Correlations between P, K, Mg, and Ca were substantial (>0.5), suggesting that these four elements are often high in the same location. As these elements are naturally abundant plant macro-and secondary nutrients this strong correlation is not surprising.

Highly correlated moss elements span multiple classes (classes listed in table 1). Iron, a plant-essential micronutrient, exhibits strong correlation with Ni, Cu, Zn (in the same class) and with Ti, Al, Si, As, Co, and Cd (none of which belong to its class). It is possible that the strong correlation of Fe with Al, Si, Ti is due to wind-blown dust and As, Cd, and Co from industrial sources (e.g. vehicular sources such as tire and brake wear, lubricant degradation). Pb was not strongly associated with any other elements.

TABLE 2:
MOSS ELEMENT DESCRIPTIVE STATISTICS

Element	Minimum	Maximum	Mean	Median	Standard Deviation	Fisher-Pearson Skewness Coefficient	# samples with values below detection
Al	142.58	1555.47	563.32	483.89	350.39	0.68	0
As	BD	0.96	0.22	0.16	0.23	0.76	4
Ba	18.76	401.79	77.31	50.46	86.32	0.93	0
Ca	2992.53	10271.97	5410.32	5052.89	1772.80	0.60	0
Cd	0.12	1.56	0.37	0.28	0.34	0.84	0
Co	0.02	2.40	0.66	0.49	0.57	0.89	0
Cr	0.91	46.51	5.42	3.89	8.73	0.53	0
Cu	4.69	55.63	17.14	14.98	10.63	0.61	0
Fe	254.54	3191.72	1131.88	1019.06	664.77	0.51	0
K	3392.46	7608.87	5520.65	5307.27	1222.83	0.52	0
Mg	1300.64	2688.25	1815.36	1594.40	436.75	1.52	0
Mn	14.24	254.44	99.04	86.74	56.36	0.65	0
Mo	BD	1.74	0.62	0.61	0.49	0.07	5
Ni	1.37	12.06	4.16	3.80	2.18	0.50	0
P	915.79	3480.32	2066.00	2108.30	518.64	-0.24	0
Pb	1.31	43.38	8.48	5.65	8.91	0.95	0
Si	39.34	349.37	187.47	186.52	75.51	0.04	0
Sr	25.29	110.81	58.85	56.60	23.66	0.29	0
Ti	13.49	155.75	53.20	47.11	33.43	0.55	0
Zn	43.08	175.56	75.87	71.84	32.72	0.37	0

*BD= below detection limits
*All elements are in units of mg/kg

TABLE 3:
SOIL ELEMENT DESCRIPTIVE STATISTICS

Element	Minimum	Maximum	Mean	Median	Standard Deviation	Fisher-Pearson Skewness Coefficient	# samples with values below detection
Al	7867.04	27109.18	13351.89	12918.48	3988.96	0.33	0
As	0.13	12.67	4.13	3.55	3.42	0.51	4
Ba	46.95	199.47	101.05	94.54	35.92	0.54	0
Ca	1744.07	6907.60	3300.44	3078.92	1133.06	0.59	0
Cd	BD	2.11	0.40	0.16	0.52	1.36	6
Co	6.63	17.26	10.24	9.32	3.03	0.92	0
Cr	30.39	95.11	52.32	51.16	16.27	0.21	0
Cu	9.65	60.52	26.53	24.02	12.75	0.59	0
Fe	13020.89	33738.89	19707.08	18187.88	5149.58	0.89	0
K	390.11	1843.98	903.62	775.96	435.25	0.88	0
Mg	2965.20	9603.68	5134.16	5046.64	1584.57	0.17	0
Mn	246.04	758.60	463.91	466.50	135.05	-0.06	0
Mo	BD	BD	BD	BD	BD	BD	25
Ni	22.20	67.34	41.97	42.23	11.61	-0.07	0
P	500.86	2413.96	1006.99	801.86	538.32	1.14	0
Pb	9.73	73.13	38.74	33.16	17.74	0.94	0
Si	348.55	2031.94	576.35	525.60	317.38	0.48	0
Sr	14.93	53.65	31.54	31.92	11.10	-0.10	0
Ti	673.79	1585.48	999.94	1056.29	206.30	-0.82	0
Zn	41.56	189.42	81.73	79.40	31.13	0.22	0

*BD= below detection limits
*All elements are in units of mg/kg

TABLE 4:
MOSS METAL CORRELATIONS

	P	K	Mg	Ca	Mo	Mn	Fe	Ni	Cu	Zn	Sr	Ti	Al	Ba	Si	As	Cd	Co	Cr	Pb
P		0.68	0.44	0.54	0.18	0.50	0.11	0.15	-0.08	0.15	0.57	0.11	0.15	0.45	0.26	0.23	-0.02	0.19	-0.08	0.56
K			0.58	0.71	0.30	0.38	0.01	-0.08	-0.26	-0.08	0.52	0.06	0.10	0.35	0.47	0.05	0.31	0.10	-0.14	0.24
Mg				0.65	0.28	0.28	0.35	0.29	0.19	0.27	0.49	0.40	0.43	0.19	0.56	0.18	-0.08	0.16	0.21	0.26
Ca					0.16	0.33	0.00	-0.03	-0.12	0.03	0.76	0.06	0.08	0.32	0.38	0.04	0.47	0.24	-0.01	0.29
Mo						-0.17	0.14	0.11	0.07	0.52	-0.08	0.10	0.13	-0.14	0.46	0.43	-0.03	-0.04	0.01	0.17
Mn							0.10	0.07	-0.04	-0.05	0.57	0.08	0.11	0.41	0.12	0.08	0.01	0.46	0.08	0.00
Fe								0.85	0.83	0.65	-0.22	0.98	0.98	-0.06	0.52	0.66	-0.09	0.70	0.78	0.37
Ni									0.89	0.61	-0.14	0.84	0.82	-0.11	0.34	0.73	-0.22	0.57	0.83	0.42
Cu										0.74	-0.29	0.79	0.76	-0.20	0.30	0.56	-0.14	0.58	0.83	0.41
Zn											-0.22	0.60	0.61	-0.14	0.38	0.54	-0.02	0.43	0.49	0.47
Sr												-0.17	-0.13	0.41	0.26	-0.13	0.07	0.09	-0.27	0.18
Ti													1.00	-0.04	0.57	0.65	-0.05	0.70	0.76	0.34
Al														-0.03	0.60	0.64	-0.04	0.70	0.72	0.34
Ba															0.17	-0.15	0.11	0.27	-0.11	0.01
Si																0.34	0.04	0.39	0.17	0.36
As																	-0.09	0.49	0.71	0.29
Cd																		0.28	0.04	-0.15
Co																			0.64	0.16
Cr																				0.17
Pb																				

*Correlations over 0.5 are shaded in gray. The darker the shading = the stronger the correlation between elements.

As a multivariate pattern recognition tool, PCA was used to extract relationships among metals from the moss and soil datasets. Significant proportions of the variability in both the moss and soil data sets were explained by their first two principal components (PCs). The total amount of variance explained by the first two PCs in the moss PCA were (70.03%): PC1 (52.23%) and PC2 (18.07%) (Fig. 5). In the moss PCA, Al, As, Cd, Co, Cr, Cu, Fe, Mo, Ni, Pb, Ti, and Zn are highly correlated with PC1; Ba, Ca, K, Mg, Mn, P, Si, and Sr concentrations are highly correlated with PC2.

The total amount of variance explained by the first two PCs in the soil PCA were (63.86%): PC1 (35.99%) and PC2 (27.87%) (Fig. 6). In the soil PCA, Soil NH_4^+/NO_3^-, As, Ca, K, Mg, and Pb are heavily loaded to PC1; Al, Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, P, Si, Sr, Ti, and Zn concentrations are highly correlated with PC2.

The EF values for the 25 different locations can be found in dot maps (fig. 7a-o). It is generally accepted that higher EF values indicate the anthropogenic sources of the element, while low EF values are indicative for natural sources, mainly pedological soil or substrates (i.e. soil parent material). The EFs for Ba, Cd, Cu, Mg, Mn, Pb, Si, Sr, and Zn point to a predominantly anthropogenic origin. The overall lower EFs (<10) found for As (with the exception of Frink Park), Co, Cr, Fe, Ni, and Ti can be element considered to originate dominantly from soil material with anthropogenic sources contributing as a minor fraction. Cadmium was highly enriched (EF>100) at Magnuson Park South, Discovery Park 1, and Kubota Gardens Natural Area 2. Lead was highly enriched (EF >100) at Northacres. Arsenic, cadmium, and lead are heavy metals on the Environmental Protection Agency's list of urban air toxins posing the greatest human health risk in urban areas, therefore these sites should be looked at in more depth for implementing proper air quality measures.

Individual soil analysis reports were created for each of the 25 locations (see Supplemental Materials). The report details concentrations for available soil nitrogen, plant-essential macro and secondary nutrients (Ca, K, Mg, P), plant-essential micronutrients (Cu, Mn, Ni, Zn), soil mineral elements (Al, Ba, Fe, Si, Sr, Ti), and environmentally important-trace elements (As, Cd, Co, Cr, Pb). All soil samples were below detection for Mo, so this was not included on the report. Soil concentrations for Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were compared to naturally-occurring background concentrations for the PSR determined by WA's Department of Ecology (San Juan, 1994). None of the soil samples exceeded background levels for Al, Fe, and Mn.

A dot map was created to show locations where soil concentrations were elevated compared to background values (fig. 8). All parks (with the exception of Kingfisher Natural Area 2, Mt. Baker Park, and West Duwamish Greenbelt 1) exceeded background levels of Pb. Two sites had 5 values that were above background concentrations (Lakeridge Park and Maplewood Playfield). Seven sites had 4 values that were above background concentrations (Discovery Park 1, East Duwamish Greenbelt 2, Harrison Ridge Greenbelt, Kinnear Park, Kubota Gardens Natural Area 1 and 2, and Northacres Park). Six sites had 3 values that were above background concentrations (Camp Long, Frink Park, Magnuson Park South, St. Mark's Greenbelt, West Duwamish Greenbelt 1, and Woodland Park). Three sites had 3 values that were above background concentrations (Kingfisher Natural Area 2, Mt. Baker Park, and Westcrest Park). The last 7 parks were above background concentrations for 1 element.

Washington State law requires that residential soils contaminated with As levels above 20ppm and Pb levels above 250ppm be remediated. None of the soil samples in this dataset exceeded the statewide contamination values. The highest levels of soil Pb concentrations was observed at Camp Long (73.13 ppm) and the highest levels of soil As concentrations was observed at Westcrest Park (12.67 ppm).

Extractable soil nitrogen ($NH4+$ and $NO3-$) values across the 25 locations are shown in fig. 9 & 10. Average extractable soil $NH4+$ levels across samples sites are: 10.93 kg-N/ha. Average extractable soil $NO3-$ levels across samples sites are: 3.07 kg-N/ha. As the soil samples were collected during the rainy season, it is possible that soil microbes readily converted $NO3$ to nitrogen gases, which diffuse back into the atmosphere resulting in lower soil concentrations.

Soil bulk density (BD) values were adequate for forest ecosystems. It is a common belief that bulk density is high in urban areas along roads and high use parks. None of the bulk density values collected showed signs of highly compacted soil. Soils rich in organic matter typically have densities of less than 0.5 g/cm3. Average BD across the 4 target ecosystem types are (standard error is listed in parentheses): 0.188 g/cm3 for Conifer Broadleaf Evergreen Mixed Forest; 0.653 (+/- 0.05) g/cm3 for Dry-Mesic Conifer and Conifer Deciduous Forest; 0.660 (+/- 0.18) g/cm3 for Moist-Mesic Conifer and Conifer Deciduous Mixed Forest; and 0.514 g/cm3 for Riparian Forest and Shrubland.

Areas for future study and restoration strategies based on most toxic metals in the moss dataset:

Top 7 air pollution 'hotspots' identified from moss samples with multiple priority heavy metals (table 5):

Location	Elements of concern	GSP Phase	# of elements on EPAs top urban toxics list	Soil elements above background concentrations
Kingfisher Natural Area #2	Al, As, Cr, Cu, Fe, Ni, Co, Pb	2	4	Cr, Ni
East Duwamish Greenbelt #1	Mo, Al, Fe, Co, Cr, Cu, As, Cd	1	3	Pb
Westcrest Park	As, Pb, Mo, Al, Co, Cr, Cu, Ni	3	4	As, Pb
East Duwamish Greenbelt #2	Cr, Al, Co, As, Ni, Mo	2	3	Cd, Cr, Ni, Pb
Mt Baker Park	Ni, Cr, Cu, Al, Fe	2	2	Cr, Ni
St. Mark's Greenbelt	Pb, Mo, Ni, Cu	3	2	Cr, Ni, Pb
Magnolia Park	Al, Fe, Pb	0	1	Pb

*EPA has identified 30 hazardous air pollutants that pose the greatest potential human health threat in urban areas (epa.gov/urban-air-toxics/urban-air-toxic-pollutants)

Currently, Kingfisher Natural Area 2 has minimal canopy coverage and bare soil conditions which leaves the site open to absorbing higher amounts of wet and dry deposition through moss communities and soil. Establishing ground cover as soon as possible is recommended to help mitigate future heavy metal deposition influences that might impact plant survivorship.

Both East Duwamish Greenbelt 1 and 2 are located within 125m of Interstate-5, so it is likely these sites experience influences from both wet and dry deposition associated with vehicular sources. East Duwamish Greenbelt 1 (Chicago St) is in the early stages of restoration and has less canopy coverage than East Duwamish Greenbelt 2 (Cloverdale St), making it more susceptible to absorbing metal deposition. Mulching and native plant installations will help to mitigate some of these influences.

Westcrest Park is a more established Dry-Mesic Conifer and Conifer Deciduous Mixed Forest compared to the other 'hotspot' locations. Given its elevation and eastern facing aspect on the slope of West Seattle it is possible this site is subject to air pollution influences from the Duwamish industrial corridor. Continued additions of mulch and compost from Cedar Grove is recommended to help 'tie up' some of the heavy metal pollutants.

Areas for future study and restoration strategies based on most toxic metals in the moss dataset (cont.):

It might be of interest to install wet deposition resin lysimeters to observe seasonal and annual deposition rates in these 'hotspot' locations (methods detailed in Bidwell, 2017). As the exact time period represented by metal accumulation in moss tissue ranges from several months to 3 years, utilizing wet deposition monitoring would provide a more accurate picture as to exact deposition rates. Resin lysimeters instrumented with ionic resin (UNIBEST Ag Manager, Walla Walla, WA) are inexpensive to make and install at GSP locations, and can be analyzed for a suite of priority metals at UW's Analytical Service Laboratory.

'Hotspot' identification based on Enrichment Factor (EF) analysis (table 6):

Location	EF elements of concern	GSP Phase	Soil elements above background concentrations
Frink Park	As	3	Cr, Ni, Pb
Magnuson South	Cd	3	Cr, Ni, Pb
Discovery Park #1	Cd	3	Cr, Ni, Pb, Zn
Kubota Gardens Natural Area #2	Cd	2	Cr, Cu, Ni, Pb
Northacres	Pb	3	Cd, Cr, Ni, Pb

Arsenic was intermediately enriched at Frink Park (EF = 14.95). Cadmium was highly enriched (EF>100) at Magnuson Park South, Discovery Park 1 (Wolf Tree 5), and Kubota Gardens Natural Area 2 (Church Envelope). Lead was highly enriched (EF >100) at Northacres. All of these elements are heavy metals on the Environmental Protection Agency's list of urban air toxins posing the greatest human health risk in urban areas these sites should be looked at in more depth for implementing proper air quality measures. Strategies include implementing wet deposition monitoring to measure seasonal and/or yearly rates.

With the exception of Kubota Gardens Natural Area #2, all of these EF 'hotspots' are in GSP phase 3. Continued additions of mulch and compost from Cedar Grove is recommended to help the soil 'tie up' some of the heavy metal pollutants at these phase 3 locations.

General soil restoration strategies for GSP:

- Tillage and soil mixing up to 8-12" deep during Phase 1/2 restoration activities to encourage soil metal dilution.

- Soil properties, including pH, organic matter content and cation exchange capacity, are known to influence the bioavailability of metals in soils. For future soil monitoring projects these measurements should be included in chemical analysis to help get a better ideas to predict bioavailable metal concentrations.

- Adding organic matter to the soil can help ‘tie up’ heavy metals chemically, reducing their availability for potential plant uptake. Soil organic matter is comprised of humus and non-humic substances. The functional groups associated with these components include phenol, carboxyl(-ate) and amino groups (Foth, 1978; Eriksson, 1989). These groups become increasingly stable at higher pH levels (Zimdahl and Skogerboe, 1977; Jones and Jarvis, 1981).

- Continued mulching and compost activities to replenish soil organic matter, enhance soil biodiversity and nutrient cycling (wood chips and coarse bark 2-4" deep incorporation) in recommended for Phase 1/2/3.

- Metals existing as cationic elements, positive change species such as Al, Ba, Cd, Co, Cu, Fe, Mg, Mn, Ni, Pb and Zn, have a greater propensity to associate with the soil and are typically less bioavailable for plants. Cationic metal solubility tends to increase at lower pH and decrease at higher pH values (Chuan et al., 1996; Thornton, 1996).

- Soil biology is key to ensuring plant establishment. By incorporating mycorrhizal inoculates (with both endomycorrhizae and ectomycorrhizae species) into bare-root and potted soil mixtures GSP increases the likelihood of native plant survivorship. Continue using Plant Success tabs for potted materials and MycoGrow for bareroot plants.

Forest planting strategies for GSP:

Phytoremediation is a cost-effective green alternative to traditional soil remediation strategies. Below is a list of PNW plant species that are known to tolerate heavy metals common in urban areas (table 7):

Scientific name	Common name	Notes	Sources
Carex obnupta	Slough Sedge	Commonly used in bioswales to treat runoff-based pollutants	Giraldo et al., 2010
Carex densa	dense sedge	Commonly used in bioswales to treat runoff-based pollutants	Giraldo et al., 2010
Pteridium aquilinum	Bracken fern	Literature shows some success for Cu, Cr	Olaifa et al., 2014; García et al., 2010
Pteris vittata	Brake fern	Literature shows effectiveness with As, Pb	Ma et al., 2001
Acer circinatum	Vine maple	Literature shows effectiveness with leachates	McCutcheon & Schnoor, 2003
Salix lucida	Pacific willow	Literature shows effectiveness with Cr and Zn	McCutcheon & Schnoor, 2003
Salix scouleriana	Scouler's willow	Study on Vashon Island indicated uptake/accumulation of Cd	Institute of Env. Research & Ed., 2003
Achillea millefolium	Yarrow	Study on Vashon Island indicated uptake and accumulation of Cd	Institute of Env. Research & Ed., 2003
Pseudotsuga menziesii	Douglas fir	Literature shows effectiveness for As, Cd, Pb	Astier et al., 2014; Bonet et al., 2016

Most of these plant species are already incorporated into GSP planting strategy. In areas where soils are significantly above background concentrations for metals, we recommend incorporating more of these plants. Below is a list of parks that are significantly above background levels for a variety of metals that should be looked into for additional plantings (table 8):

Elements significantly above background soil levels	Location
As, Pb	Westcrest Park
As, Pb, Zn	Camp Long
Cd, Cr, Ni, Pb	East Duwamish Greenbelt #2
Cd, Pb	Lakeridge Park
Cr, Cu, Ni, Pb	Kubota Gardens Natural Area #2
Cr, Cu, Ni, Pb, Zn	Maple Wood Playfield
Cr, Ni	West Duwamish Greenbelt #1
Cr, Ni, Pb	Magnuson South, Northacres Park, St. Mark's Greenbelt
Cr, Ni, Pb, Zn	Harrison Ridge Greenbelt, Kinnear Park
Cr, Pb, Zn	Discovery Park #1, Kubota Gardens Natural Area #1, Woodland Park
Ni	Kingfisher Natural Area #2
Ni, Pb	Frink Park
Pb	East Duwamish Greenbelt #1, Golden Gardens, Kingfisher Natural Area #1, Magnolia Park, Northeast Queen Anne Greenbelt, West Duwamish Greenbelt #2

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