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ARTICLE

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Heavy metals in moss guide environmental justice investigation: A case study using community science in Seattle, WA, USA

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Abstract

Heavy metal concentrations often vary at small spatial scales not captured by air monitoring networks, with implications for environmental justice in industrial-adjacent communities. Pollutants measured in moss tissues are commonly used as a screening tool to guide use of more expensive resources, like air monitors. Such studies, however, rarely address environmental justice issues or involve the residents and other decision makers expected to utilize results. Here, we piloted a community science approach, engaging over 55 people from nine institutions, to map heavy metals using moss in two industrial-adjacent neighborhoods. This area, long known for disproportionately poor air quality, health outcomes, and racial inequities, has only one monitor for heavy metals. Thus, an initial understanding of spatial patterns is critical for gauging whether, where, and how to invest further resources toward investigating heavy metals. Local youth-led sampling of the moss *Orthotrichum lyellii* from

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trees across a 250 × 250 m sampling grid ($n = 79$) and generated data comparable to expert-collected samples ($n = 19$). We mapped 21 chemical elements measured in moss, including 6 toxic "priority" metals: arsenic, cadmium, chromium, cobalt, lead, and nickel. Compared to other urban *O. lyellii* studies, local moss had substantially higher priority metals, especially arsenic and chromium, encouraging community members to investigate further. Potential hotspots of priority metals varied somewhat but tended to peak near the central industrial core where many possible emission sources, including legacy contamination and converge. Informed by these findings, community members successfully advocated regulators for a second study phase—a community-directed air monitoring campaign to evaluate residents' exposure to heavy metals—as is needed to connect moss results back to the partnership's core goal of understanding drivers of health disparities. This follow-up campaign will measure metals in the PM_{10} fraction owing to clues in the current study that airborne soil and dust may be locally important carriers of priority metals. Future work will address how our approach combining bioindicators and community science ultimately affects success addressing longstanding environmental justice concerns. For now, we illustrate the potential to co-create new knowledge, to help catalyze and strategize next steps, in a complex air quality investigation.

KEYWORDS
air toxics, bioindicators, citizen science, civic science, coarse particulate matter, community science, Duwamish Valley, environmental justice, hazardous air pollutants, heavy metals, moss, PM_{10}

INTRODUCTION

The World Health Organization estimates that poor air quality causes 4.2 million premature deaths globally each year (Cohen et al., 2017). Understanding the spatial distributions of hazardous air pollutants (HAPs; "air toxics") is of international concern; even low levels of HAPs, including heavy metals, are associated with significant health risks such as various cancers, heart attack, stroke, asthma attacks, and neurological deficits (Jaishankar et al., 2014; Landrigan et al., 2018; USEPA, 2014a). According to the US Government Accountability Office (2020), the ability to characterize HAPs at local scales is a critical need poorly supported by an aging air monitoring infrastructure. Declining funds and the high cost of regulatory-grade instruments makes for widely spaced monitoring networks, resulting in extensive areas of unknown exposure and environmental health risk (Marshall et al., 2008; Pakbin et al., 2010; Sarnat et al., 2010; Strum & Scheffe, 2016).

To inexpensively fill these gaps for heavy metals, scientists commonly measure concentrations in moss or lichen tissue (hereafter, "bioindicators"; e.g., Giordano et al., 2009; Massimi et al., 2019; Neitlich et al., 2017). Without roots or a protective outer cuticle, moss and lichens absorb water, nutrients, and co-occurring toxics from the atmosphere, making them a valuable first-pass screening tool in urban areas (e.g., Donovan et al., 2016; Messager et al., 2021). As with other low-cost sensors, bioindicator data help optimize the use of limited resources, like air monitors or even investigators' time and attention (Donovan et al., 2016; Gatziolis et al., 2016). Air monitors are ultimately required to determine whether pollution levels pose human health risks or exceed regulatory thresholds, making their efficient use in air investigations essential.

Understanding fine-scale patterns may be particularly important in industrial-adjacent neighborhoods (Government Accountability Office, 2020). Despite their demonstrated efficacy, however, bioindicators are rarely used in investigations of environmental justice (but see Contardo et al., 2018; Steiner et al., 2021), commonly defined as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations and policies" (USEPA, 2021). Furthermore, affected residents and other decision makers are not typically involved in bioindicator research even though many collaborative environmental health studies report higher synergy, creativity, and efficiency, ultimately translating into greater research impacts (Cordner et al., 2019; English et al., 2018). By adopting a community science approach that substantively engages stakeholders, two distinct opportunities are created—for community engagement in the participatory process of environmental research itself, and in co-producing knowledge directly informing decisions that improve environmental conditions (Charles et al., 2020).

In this case study, community leaders convened a diverse partnership of public and nonprofit organizations, led by residents and including local youth, to co-produce new knowledge addressing environmental justice concerns in the industrial-adjacent Georgetown and South Park (SP) neighborhoods in Seattle, WA, USA. Both are disproportionately burdened with poor health outcomes, air quality, and racial inequities, relative to other Seattle neighborhoods (Daniell et al., 2013; Gould & Cummings, 2013; Min et al., 2019; Schulte et al., 2015; U.S. Department of Health and Human Services, 2008; Washington State Department of Health, 2021). Prior data suggest heavy metals may increase local cancer and noncancer risk (Puget Sound Clean Air Agency [hereafter "PSCAA"] and Washington State Department of Ecology, 2003; U.S. Department of Health and Human Services, 2008; USEPA, 2019) although only one monitor in the area measures heavy metals (Figure 1). Our study objectives included the following: (1) determining whether community and expert-collected moss samples indicate similar pollution patterns, (2) comparison with other urban moss datasets as context for local values, and (3) mapping and summarizing spatial distributions of heavy metals in moss. We discuss how results guide the course of investigation and directly informed three types of community action, including the successful initiation of a follow-up air monitoring campaign.

METHODS

Case study background

The SP and Georgetown communities are located on the shores of the Duwamish River in the Duwamish Valley (DV) airshed (Figure 1). The Duwamish River has been Seattle's main industrial corridor since the early 20th century (Cummings, 2020), which has created a legacy of potentially harmful pollution to air, soils, and water. In 2001, an 8-km segment of the river, parts of which are adjacent to study area, was designated an active USEPA Superfund site due to contamination by polychlorinated biphenyls, carcinogenic polycyclic aromatic hydrocarbons, dioxins and furans, and arsenic in river sediments (USEPA, 2014b). In addition, over 150 Washington Model Toxics Control Act (MTCA; state "superfund") contaminated sites have been named within or just adjacent to the study area, with clean-up completed at about 25% of them (Washington Department of Ecology, 2021). The area also includes many unpaved roads, railway lines, waterway traffic, an airport (KCIA), highways with high levels of commuter and truck traffic, and several types of industrial facilities—some in place for over 100 years that manufacture or recycle materials such as glass, metal, and cement (Cummings, 2020). These industrial and transportation areas are interspersed with single- and multifamily housing, home to approximately 5600 Georgetown and SP residents (City of Seattle, 2018).

The long history of industrial pollution in Seattle is linked to poor health outcomes for residents (City of Seattle, 2018; Gould & Cummings, 2013; Min et al., 2019; Washington Department of Health, 2021). Major health concerns include higher rates of asthma and diabetes and lower life expectancies in the DV than city averages (City of Seattle, 2018; Gould & Cummings, 2013). Environmental factors map onto social vulnerabilities, resulting in cumulative health impacts that are higher than the rest of Seattle (Gould & Cummings, 2013). In the 98108 ZIP code including Georgetown and SP, 73.8% of residents are non-White (compared to 36.2% in Seattle city-wide), 34.7% are foreign-born (18.5% city-wide), 20.9% live below the poverty level (11.0% city-wide), and just 32.2% of residents 25 years and older hold a bachelor's degree or higher (64.0% city-wide; US Census, 2019).

Monitoring sites and standards

Heavy metals associated with particulate matter (PM) include fine inhalable particles with diameter sizes ≤2.5 μm (i.e., $PM_{2.5}$), inhalable particles with a diameter size ≤10 μm (PM_{10}), and total suspended particulates (TSP). PM_{10} is considered hazardous to human health, with the finer fractions posing a higher risk due to deeper airway penetration (Brown et al., 2013). Both $PM_{2.5}$ and PM_{10} are criteria pollutants, meaning their mass concentration in the atmosphere is regulated by federal ambient air standards. Similar standards do not exist for specific heavy metals except lead (Pb) in TSP.

There are currently two PM monitoring stations in the DV: the Duwamish (DW) site northwest of our moss sampling locations, and the SP site at the north end of that neighborhood (Figure 1). Both DV stations measure

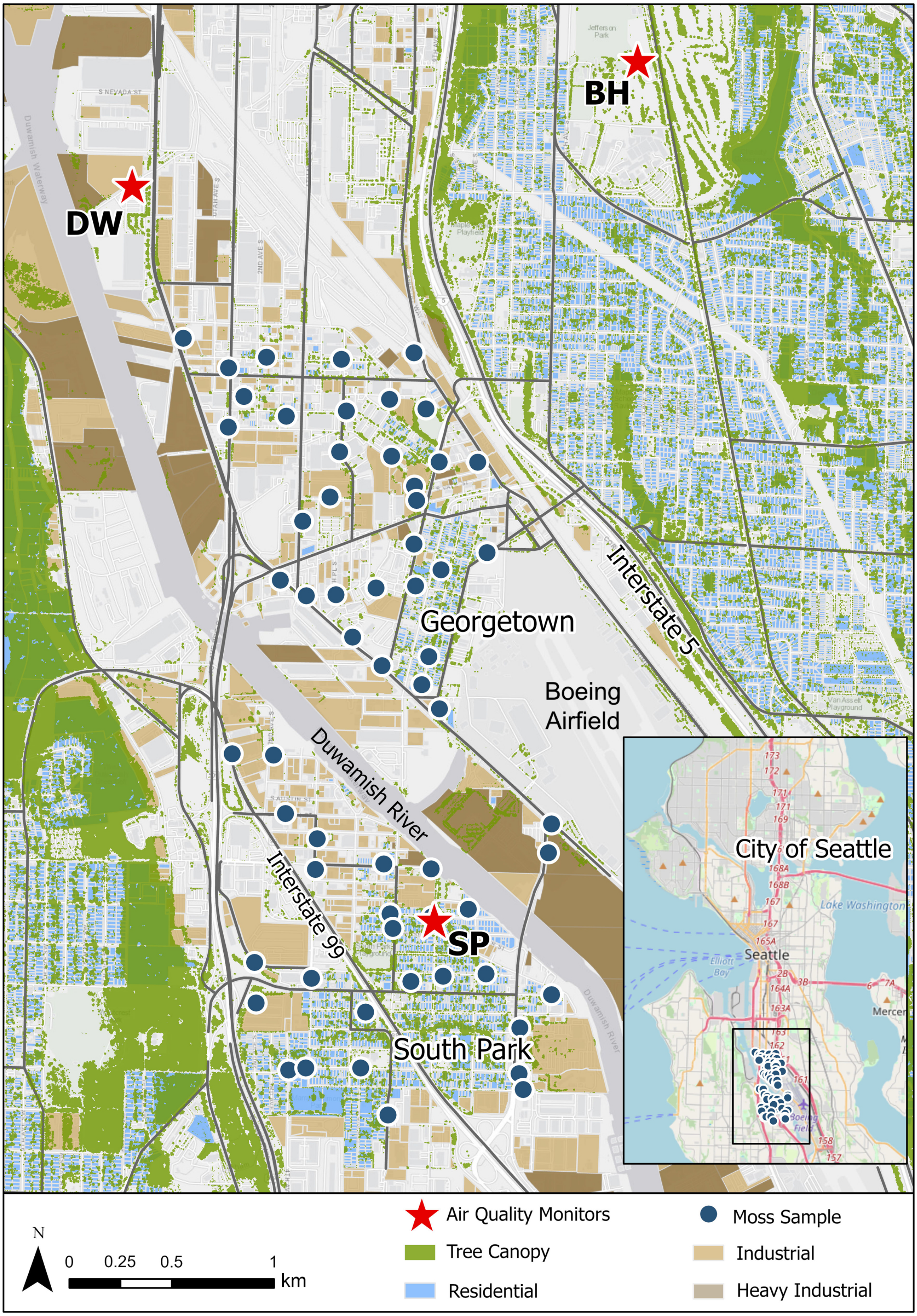


FIGURE 1 Map of the Duwamish Valley showing moss sampling locations and air quality monitors relative to major land use types (BH = Beacon Hill, National Air Toxics Assessment site; includes speciated $PM_{2.5}$ and PM_{10}; DW = Duwamish monitor, measures speciated $PM_{2.5}$; SP = South Park monitor, total $PM_{2.5}$ only)

the $PM_{2.5}$ size fraction only, with "speciated" data (i.e., specifying concentrations of constituent heavy metals and other co-occurring toxics) available for just the DW site. The closest PM_{10} measurements come from Seattle's single National Air Toxics Trends Site (NATTs) in the Beacon Hill (BH) neighborhood, about 1.5 km away above the DV river basin. This site measures many toxics, including heavy metals, in both $PM_{2.5}$ and PM_{10}, and is used as a reference site to broadly represent air quality across Seattle's urban residential areas (PSCAA, 2019). As larger particles (i.e., TSP) tend to be lower risk for health consequences, they are not criteria pollutants and are not often monitored outside of special studies.

Study partners and roles

Over 55 people from nine institutions, including community-based organizations, universities, and government agencies, played key roles in this project (see *Acknowledgements*). Partnerships and collaborative process are detailed in Derrien et al. (2020). In brief, two organizations led youth engagement: the Duwamish Valley Youth Corps (DVYC), a program of the Duwamish River Community Coalition (DRCC) that engages high-school-aged youth in paid local environmental justice-oriented projects; and the Duwamish Infrastructure Restoration Training program (DIRT Corps), a green infrastructure workforce training program for adults. Study partners across institutions contributed to all facets of the study initiation, conception, sampling design, protocol development, youth engagement, data collection, and sample preparation (Derrien et al., 2020). Data analysis and interpretation were completed by agency and university partners.

Field sampling and preparation

Moss sampling protocols were adapted from prior studies using the widespread epiphytic (i.e., "tree-dwelling") moss species *Orthotrichum lyellii* (Donovan et al., 2016; Gatziolis et al., 2016). Our study area was about 2 km by 4 km. We collected the moss from a 250 × 250 m grid across the study area to ensure samples were well-distributed, although sample coverage along riverside industrial areas was sparser than intended due to lack of trees and target moss (Figure 1). Moss was collected at the suitable tree nearest the centroid of each grid cell at a height between 1 and 3 m. We used a "train-the-trainer" approach where scientists experienced in leading moss studies trained leaders of the DVYC and DIRT Corps, who then trained youth participants (Derrien et al., 2020). The DVYC led moss sampling excursions on four warm, dry days in 2019 (25 May, 1, 4, and 8 June), working in five teams led by 3–5 youth, each accompanied by an adult study partner. Participants met the following week in a local high school science laboratory to harvest the upper two-thirds of living moss stems for heavy metals analysis (Gatziolis et al., 2016).

Sampling QC/QA

To assess sampling precision, the youth-led teams immediately collected a replicate moss sample at 18 sites where ample moss was available. Their final analytical dataset had 79 samples from 61 grid cells. As reported initially in Derrien et al. (2020), measurements of heavy metals concentrations among same-day youth replicates were highly repeatable. To check sampling accuracy, experts resampled 19 grid cells although this occurred about 2 weeks later on 13 June 2019 due to scheduling difficulties. While Derrien et al. (2020) found sufficient statistical agreement between youth–expert samples to support confident use of the youth's dataset in this study, they noted priority metals were somewhat lower in expert samples. Here, we investigated further by examining how well metal concentrations in the two datasets agreed spatially and by reviewing information on timing and other circumstances potentially affecting sample collection.

Laboratory preparation and analysis

All moss samples were sealed and mailed to the US Forest Service Grand Rapids, MN laboratory where they underwent the same treatment. Samples were prepared for heavy metals analysis by oven drying at 40°C for 24 h and homogenizing by grinding to a fine powder (IKA tube mill, 1-min grinding time for each sample at 15,000 rpm). A 0.500-g subsample of each moss sample was processed using a modified microwave-assisted digestion with 10 ml concentrated $HNO_3 + 2$ ml 30% $H_2O_2 + 2$ ml concentrated HCl (CEM Corp., 2019). An overnight predigestion of the samples with added reagents was done at room temperature. Following the microwave-assisted digestion cycle, digests were transferred by rinsing with deionized water to 50-ml volumetric flasks, diluted to volume with deionized water, and filtered through 0.45-μm membrane filters into plastic storage bottles prior to analysis. Concentrations of 25 elements in total were measured by inductively coupled plasma optical emission spectrophotometry (Thermo 7000 series dual-view [axial and radial] ICP-OES).

Lab QC/QA

Quality control steps included use of method blanks, instrument calibration standards, instrument performance check standards, and reference lichen samples. The measurement quality objectives are the same as the confidence and tolerance levels that accompany each standard reference material or check standard certification sheet. Quality control/quality assurance (QC/QA) for analysis of moss tissue in our study follows our prior work (Gatziolis et al., 2016) and is described in detail in Appendix S1.

Data analysis

We used the youth-collected dataset to map 21 elements in moss tissues, leaving out 4 macronutrients of limited relevance (Table 1). Analyses focused on six heavy metals (hereafter, "priority metals") commonly associated with negative ecological and human health effects: arsenic, cadmium, chromium, cobalt, nickel, and lead. All are considered high priority for urban areas nationally (Agency for Toxic Substances and Disease Registry, 2019; USEPA, 2014a) and all but cobalt locally (PSCAA, 2019; PSCAA and University of

TABLE 1 Summary of element concentrations in the youth's moss collections ($n = 79$)

Element	Min	Max	Mean	Median	Skewness	Kurtosis	PC1 (ρ)	PC2 (ρ)
Priority metals (mg/kg)								
Arsenic (As)	0.322	3.214	1.134	0.929	1.528	2.121	0.88	0.08
Cadmium (Cd)	0.126	1.96	0.541	0.410	1.542	2.053	0.66	0.68
Chromium (Cr)	4.337	61.055	15.969	11.484	2.034	4.183	0.94	−0.19
Cobalt (Co)	0.431	11.738	1.692	1.235	3.898	20.997	0.95	−0.14
Lead (Pb)	5.906	110.641	21.964	16.262	2.591	8.972	0.87	0.07
Nickel (Ni)	1.956	58.961	7.406	6.152	5.234	35.885	0.92	−0.23
Macronutrients (%)								
Calcium (Ca)	0.395	1.371	0.792	0.783	0.615	0.474	0.68	0.14
Magnesium (Mg)	0.08	0.308	0.177	0.165	0.673	−0.238		
Phosphorus (P)	0.118	0.381	0.208	0.206	0.458	0.526		
Potassium (K)	0.361	0.736	0.544	0.546	0.219	−0.326		
Sulfur (S)	0.103	0.284	0.17	0.160	1.086	0.763		
Other elements (mg/kg)								
Aluminum (Al)	741.756	8085.26	2242.219	1742.917	1.9	3.935	0.89	−0.18
Barium (Ba)	22.708	221.088	65.975	58.840	2.026	6.141	0.7	−0.16
Boron (B)	14.948	112.116	40.205	33.757	1.448	2.073	0.44	0.38
Copper (Cu)	15.565	114.565	40.417	34.189	1.512	1.925	0.8	−0.1
Iron (Fe)	891.876	16,287.047	3685.643	2654.522	2.279	6.332	0.92	−0.17
Manganese (Mn)	30.872	505.345	120.816	93.967	2.449	7.323	0.74	−0.17
Molybdenum (Mo)	0.736	6.658	2.199	1.724	1.756	3.317	0.89	−0.19
Selenium (Se)	BDL	1.428	0.122	NA	NA	NA	NA	NA
Silicon (Si)	73.333	3476.024	1778.626	1823.603	0.063	1.959	0.65	−0.14
Sodium (Na)	171.04	859.82	375.659	335.297	1.251	1.272	0.62	−0.02
Strontium (Sr)	16.449	71.289	40.59	39.796	0.304	−0.119	0.55	0.06
Titanium (Ti)	21.634	521.802	148.217	105.711	1.377	1.515	0.77	−0.13
Vanadium (V)	2.295	25.494	6.977	5.559	1.779	3.588	0.9	−0.17
Zinc (Zn)	64.118	736.177	198.198	161.795	1.96	5.055	0.73	−0.06

Note: Principal components (PC) 1 and 2 are Spearman's rank correlations between elements and axis scores from the first two axes found using principal component analysis (PCA). Macronutrients of minor relevance were not included in the PCA.

Abbreviations: BDL, below detection limit; NA, not available.

Washington, 2010; U.S. Department of Health and Human Services, 2008; Wu et al., 2011).

Comparison to reference datasets

As heavy metals are one of several pollutant groups of concern in the DV, we conducted an initial screening step to gauge whether investigating them further was warranted. We compared priority metals to similar *O. lyellii* datasets from Seattle City Parks ($n = 25$; Bidwell, 2018; Bidwell et al., 2019; Appendix S2: Figure S1) and residential areas throughout Portland, Oregon ($n = 346$; Donovan et al., 2016; Gatziolis et al., 2016). Sampled areas occur at similar elevations and human population densities in the "Dry Summer Subtropical Zone" of the Pacific Northwest (PNW), characterized by cool, wet winters and mild, relatively dry summers (Chen & Chen, 2013). Datasets used similar field methods, digestion, and ICP spectroscopy techniques. One notable difference was sampling season; the DV was sampled in summer and reference datasets in winter. We used the 95th percentiles for priority metals measured in Portland as points-of-comparison because these thresholds coincided with high outliers in that dataset, some of which exceeded local air concentration benchmarks when evaluated using air instruments.

Spatial distributions

We used principal component analysis (PCA) based on the correlation structure among measured elements to identify and characterize major metals gradients in the youth's dataset. We define "gradients" as distinct distribution patterns involving correlated responses of multiple elements, represented by axes (i.e., principal components) in PCA. First, we $\log_{10}$-transformed elements with highly skewed distributions (skewness >0.5) to meet the normality and linearity assumptions of PCA. Second, we performed PCA on the scaled and centered correlation matrix of the six priority metals using function "stats::prcomp" in R version 4.0.2 (R Core Development Team, 2020). Third, we applied graphical vector overlays and calculated Spearman's rank correlation coefficients (ρ) to estimate how strongly all individual elements related to scores along each PCA axis (i.e., axis scores). Relationships between PCA axes and the other measured elements offer possible clues about the nature or origin of priority metals.

To evaluate spatial agreement between the youth- and expert-collected samples, we performed another set of PCA analyses separately for each dataset using only the subset of 17 sites having both youth and expert samples. To test agreement of youth and expert PCA scores, we compared axis scores using Procrustes analysis (Peres-Neto & Jackson, 2001). We used the R function "vegan::procrustes" with symmetric solutions, calculated permutation p values using 9999 permutations, and calculated Procrustean congruence (R_P) as one minus the Procrustes sum-of-squared-errors (rather than the square-root of this quantity, as in software defaults) to better interpret it as a "coefficient of determination"-like statistic on a 0–1 scale. Perfect agreement among students' and experts' gradient scores would give a Procrustes fit (R_P) approaching 1 and a permutation p value $<< 0.01$, while agreement no better than random would give R_P near 0, and $p >> 0.05$.

Finally, we used the youth's data to quantify the spatial distribution of pollution gradients by mapping scores from statistically significant PCA axes at moss sample locations, as well as by interpolating scores as a continuous surface between sites using spatial kriging. For kriging, we fit an empirical variogram model using the observed values to parameterize a final variogram model based on Gaussian covariance describing the spatial decay of similarity among sites (R functions "gstat::variogram" and "gstat::vgm"). We assumed the Gaussian process was constant across the study area. From the variogram, we applied ordinary kriging ("gstat::krige") to predict interpolated values for unsampled locations between sites. Predicted values and their variances were used to construct 95% CI describing spatial uncertainty in the kriged PCA values. All spatial predictions were on a 10,000-cell grid in Albers equal-area projection covering the study area.

RESULTS

Our final QC/QA check comparing PCA scores of youth versus expert-collected samples indicated highly significant agreement ($p = 0.001$) and sufficient spatial correlation (Procrustes fit $R_P = 0.42$). Therefore, all remaining analyses are based solely on the youth's data.

Comparison to reference datasets

Overall, priority metals in DV moss were significantly much greater than the Seattle City Parks and Portland residential datasets (t tests; $p < 0.001$). The most extreme cases were arsenic and chromium, for which nearly all DV concentrations exceeded Portland's 95th percentiles (Figure 2). Concentrations of cobalt, lead, nickel, and cadmium in the DV exceeded the Portland thresholds 59%, 55%, 43%, and 22% of the time, respectively.

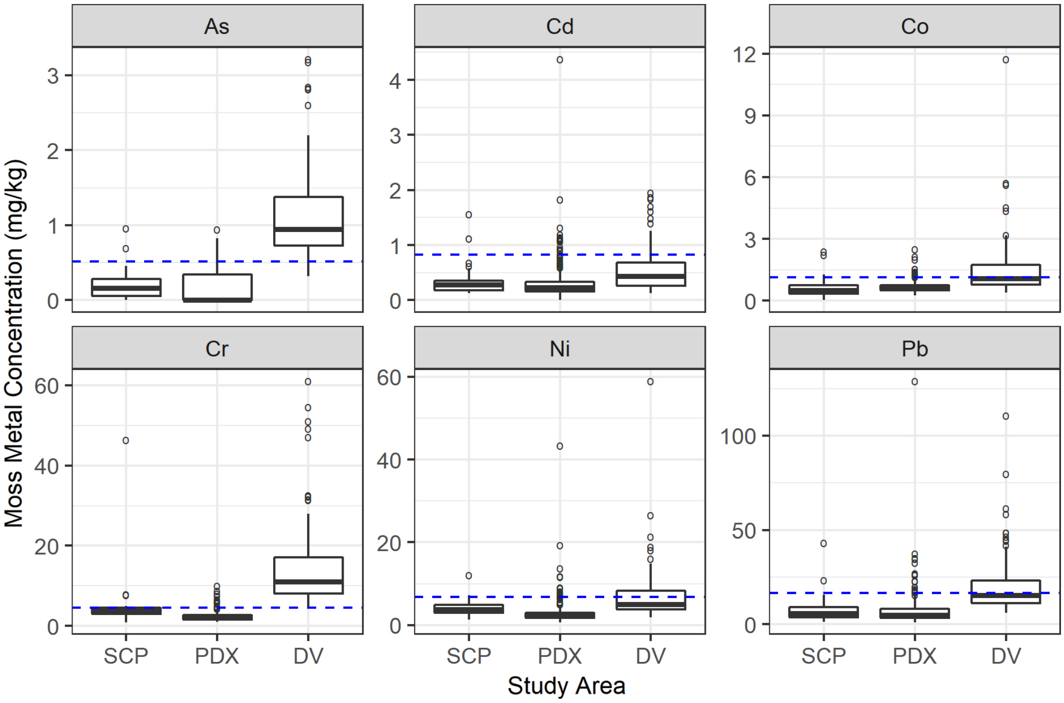


FIGURE 2 Boxplots comparing priority metal concentrations in this study (DV = Duwamish Valley) with Seattle City Parks (SCP) and Portland residential areas (PDX). Blue dashed lines indicate the Portland 95th percentiles.

Moreover, medians and 25th percentiles for DV samples were relatively elevated compared to reference datasets. The statistical sampling distributions of most elements in the DV were highly positively skewed, which typically indicates anthropogenic (vs. natural geogenic) emission sources (e.g., Solt et al., 2015; Figure 3; Appendix S2: Figure S2).

Spatial distributions

Concentrations of most elements peaked in the industrial core along the river's banks west and northwest of Boeing Airfield and east of U.S. Highway 99, the main N-S highway crossing the river (Figure 3; Appendix S2: Figure S2). Priority metals were strongly correlated, such that sites with relatively high values for one tended to be high for the others (Appendix S2: Figure S3). The first PCA axis ("PC1," hereafter) supports this observation, explaining 76.5% of the variation in priority metals concentrations in the youth's dataset ($p = 0.001$; Figure 4). We interpreted PC1 as the dominant gradient of elemental concentrations based on strong positive associations (Spearman's correlations, $r > 0.75$) with nearly all measured elements (Table 1), indicating PC1 scores increased as elemental concentrations increased. Therefore, kriged PC1 scores shared common features with the maps for most individual metals (Figure 5). We also noted chemical elements indicative of soil and fugitive dust (i.e., aluminum, calcium, iron, silicon, strontium, and titanium; Charlesworth et al., 2011; Kim & Hopke, 2008, Watson & Chow, 2000) correlated moderately to strongly with priority metals, besides cadmium, when considered both individually (mean Pearson correlation coefficient, $r \geq 0.65$; Appendix S2: Figure S3) and collectively as PC1 (Spearman's rank correlations, $r = 0.55$–0.92; Table 1).

The second PCA axis ("PC2," hereafter) was nonsignificant, explaining only an additional 12.6% of the variation in priority metals (Figure 4). Therefore, we interpret it cautiously as a weak gradient with a unique elemental signature characterized by cadmium and boron concentrations (Spearman's correlations $r = 0.68$ and 0.38, respectively). PC2 was also weakly positively associated with other elements like arsenic and strontium (Table 1).

DISCUSSION

This was the first study of its kind in which residents, including local youth, collected and prepared moss samples for laboratory analysis with minimal oversight by scientific experts. Our results supported Derrien et al.'s (2020) conclusion that trained community and youth groups can collect scientifically viable moss tissue datasets. To further clarify Derrien et al.'s (2020) finding of somewhat lower priority metals concentrations in

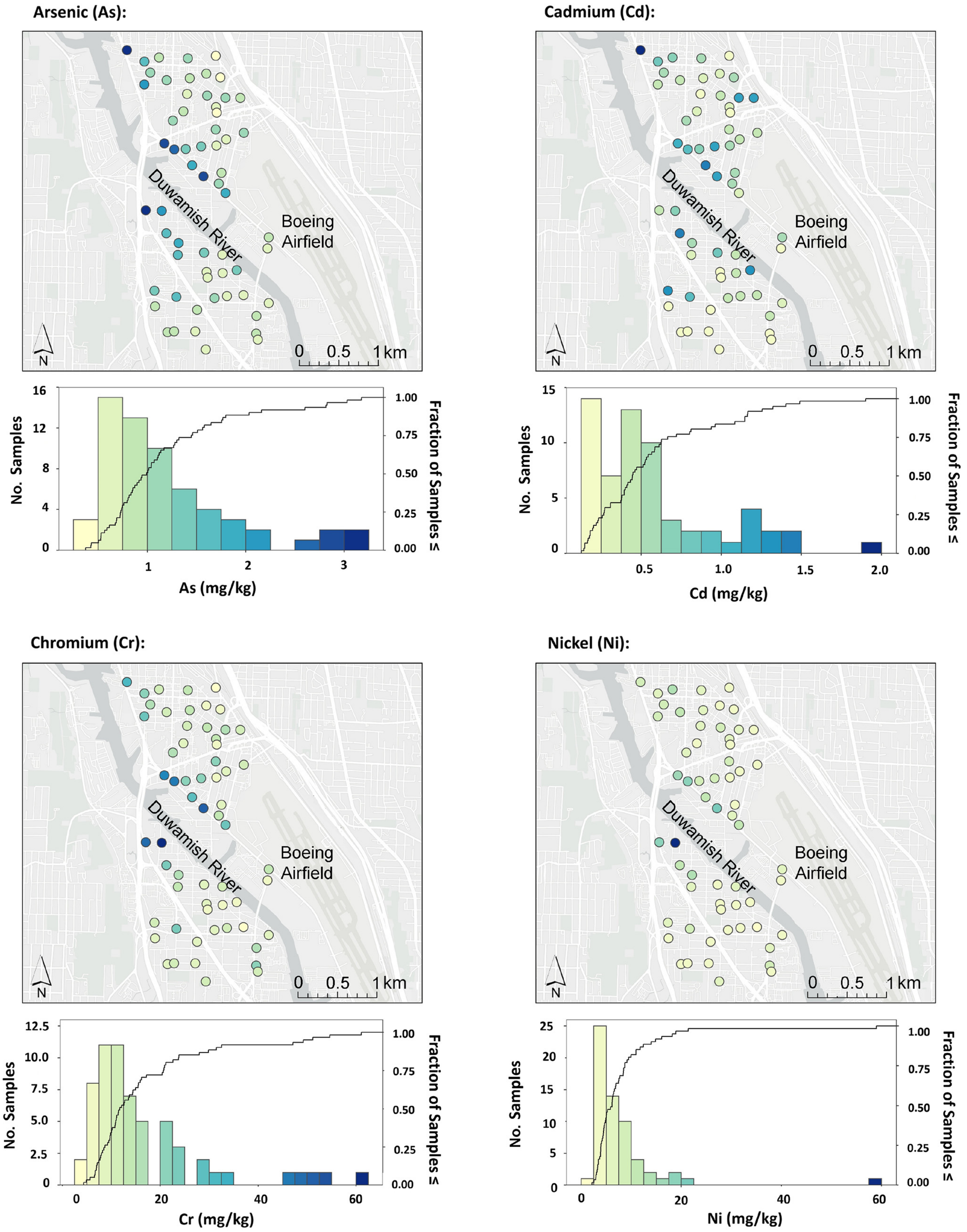
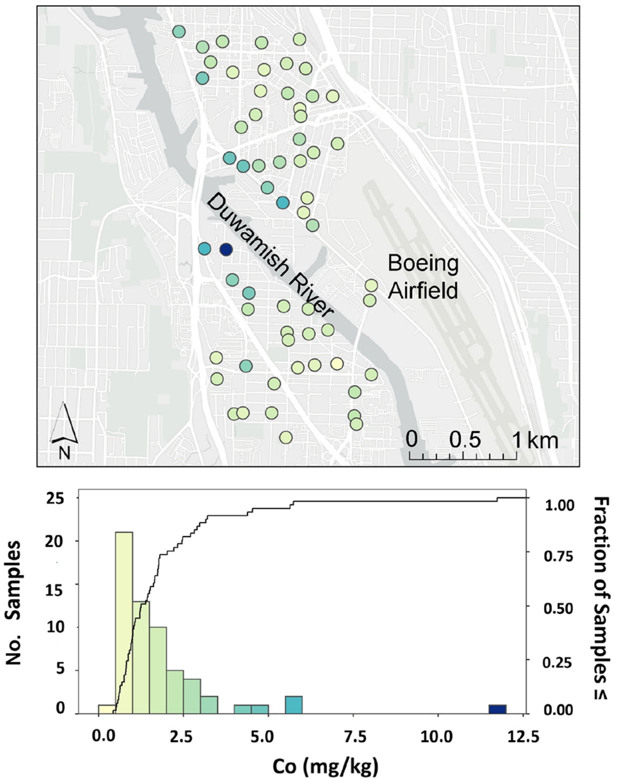


FIGURE 3 Dot maps and histograms showing concentrations of priority metals in DV moss. Black lines on the histograms are cumulative distribution curves.

Cobalt (Co):



Lead (Pb):

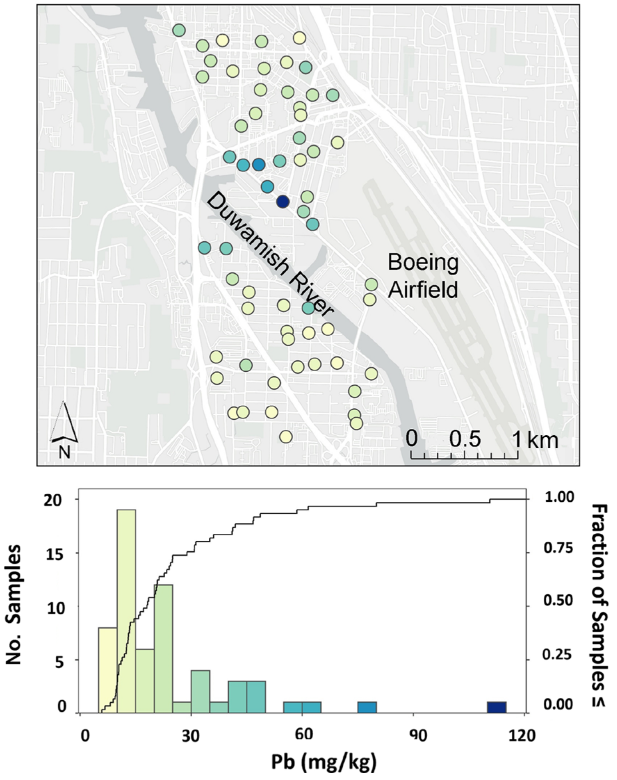


FIGURE 3 (Continued)

expert- versus youth-collected samples, we confirmed these datasets captured similar spatial information when comparing relative rather than absolute concentrations. We suspect systematic differences were caused by a flash thunderstorm occurring after most youth but before most experts collected samples rather than a data quality issue. Conditions were mainly hot and dry during the 3 weeks of fieldwork, allowing PM to accumulate on bioindicator surfaces where driving rain can easily wash it off (i.e., "wash out events"; Čeburnis & Valiulis, 1999; Giordano et al., 2009).

Comparison to reference datasets

In our initial screening step comparing concentrations of priority metals in local and reference moss datasets, we interpreted our finding of much higher values in DV moss as strong justification for their further investigation. Our comparison is imperfect; for instance, datasets were collected in different seasons, which adds uncertainty to the comparison that is difficult to predict (e.g., Giordano et al., 2009; Saitanis et al., 2013). Nevertheless, we cannot easily assume weather or other unmeasured factors fully explain the large differences we observed (Figure 2). Furthermore, while spatially limited, prior studies using air monitors measured high priority metals concentrations at certain locales in the DV, including Georgetown (discussed in *Synthesis and recommendations for follow-up air monitoring*), which helped motivate the current study to characterize spatial patterns.

Spatial distributions

The moss-based maps provide a first look at local-scale priority metals concentrations invaluable for guiding next steps of the investigation (Figures 3 and 5). The dense grid of moss samples shows high spatial variability that the single local air monitoring site ("DW"; Figure 1; Appendix S2: Figure S1), or even a few hypothetical monitoring sites for that matter, could not possibly describe. While our moss data (in milligrams per kilogram moss tissue) are not easily equated with air concentrations measured at DW, we noted the monitor did not detect arsenic at all (e.g., PSCAA, 2018, 2019). This was surprising because several DV air investigations (e.g., King County, 2015; PSCAA and Washington State Department of Ecology, 2003; USEPA, 2014b, 2019) in addition to this study (Figure 2) suggest substantial arsenic concentrations in the DV. We present a testable hypothesis potentially explaining this discrepancy in *Synthesis and recommendations for follow-up air monitoring* and will continue focusing on arsenic in future work.

Overall, metals (as represented by PC1) tended to peak centrally where many extant emission sources (industrial, highway, waterway, and air travel) co-occur

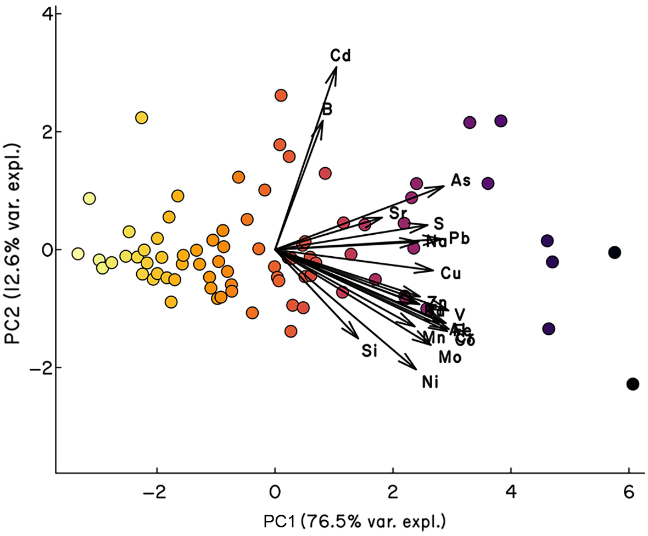


FIGURE 4 Biplot of scores from principal component analysis (PCA) of the six priority heavy metals (As, Cd, Cr, Co, Ni, and Pb), with other measured elements shown as overlays. PCA axis 1 ("PC1") was the dominant axis of elemental concentration, with nearly all measured elements having strong positive correlations as indicated by direction and length of vector arrows. Each point represents one moss sample site, colored by relative value of PC1 axis scores (yellow = lowest to purple = highest). Concentrations were $\log_{10}$-transformed to linearize relationships and make highly skewed distributions more symmetrical.

with legacy contamination of the soil accumulating over more than 100 years of industrial and transportation activity. Dispersion from this main area and other emission sources are affected by several factors including the dominant winds, which come from the south and southwest (approximately 32% of the year) and north and northeast (about 23%; Office of the Washington State Climatologist, 2005). Furthermore, many unvegetated areas, including contaminated MTCA sites, exist near the hotspot along with unpaved roads where heavy truck traffic can track out dust and exacerbate re-entrainment into the air (Charlesworth et al., 2011; Roberts et al., 1975; Zhao et al., 2017). Accordingly, the close association between priority metals and elemental indicators of soil and fugitive dust (e.g., aluminum, calcium, iron, silicon, strontium, and titanium) suggests they may be part of the same particles or otherwise have common origins.

Efforts to identify specific sources affecting residential air quality lie beyond the scope of this study and will be complicated by the density of nearby emission sources and potential for PM to continue mixing and affecting the air long after its initial emission (Johnston & Cushing, 2020). How proximity to the central industrial area and other environmental factors correlate with metals levels in the neighborhoods' residential zones is the focus of a follow-up study already underway (Kondo et al., 2022). These results, along with findings from community actions focused on discerning the potential health risk of the metals, as described in the following section, will support decision making on how to prioritize and approach unresolved questions about pollution sources.

The weak pattern indicated by PC2 seemed highly influenced by a single sample from the northwestern edge of the study area (Figure 5). This site had a unique elemental signature relatively high in cadmium, boron, arsenic, and selenium (Table 1, Figure 3; Appendix S2: Figure S2b,c,f,p) that was also detected in an expert resample collected a week later (data not shown). Follow-up work would be needed to understand the geographic scope and relevance of this finding. This unique signature could indicate one of several possibilities: A distinct emission source just north of our sampling grid, an area-of-effect smaller than the resolution of our sampling grid, or simply idiosyncratic conditions at the particular tree where youth and adult study partners collected moss. Regardless, it is clear PC2 does not describe a major pollution gradient in the current study area and is considered low priority for the community's next steps investigating air concerns in Georgetown and SP.

Community actions

A core tenet of community science is that endeavors directly empower communities and support consequential collective actions (Charles et al., 2020). Partners' ongoing attention to study design and outputs ensured that knowledge gaps being explored would result in actionable science addressing the specific needs of the Georgetown and SP communities. Study processes and outputs resulted in three types of community action:

1. *Youth empowerment and training*: This work inspired youth actions in their communities, including mentoring other youth, leading independent data analysis, and presenting this study's findings to community organizations including the mayor and city council. Youth engaged in and led many of the advocacy, partnership, and mitigation actions detailed below. Furthermore, the youth engaged in subsequent programming with project partners, including a second moss sampling campaign in summer 2021, expanding the sampling area and resampling areas of interest.
2. *Mitigation*: Our findings inform where to target near-term mitigation strategies to help improve conditions in the DV using green infrastructure (such as green walls and ongoing tree planting efforts) in partnership

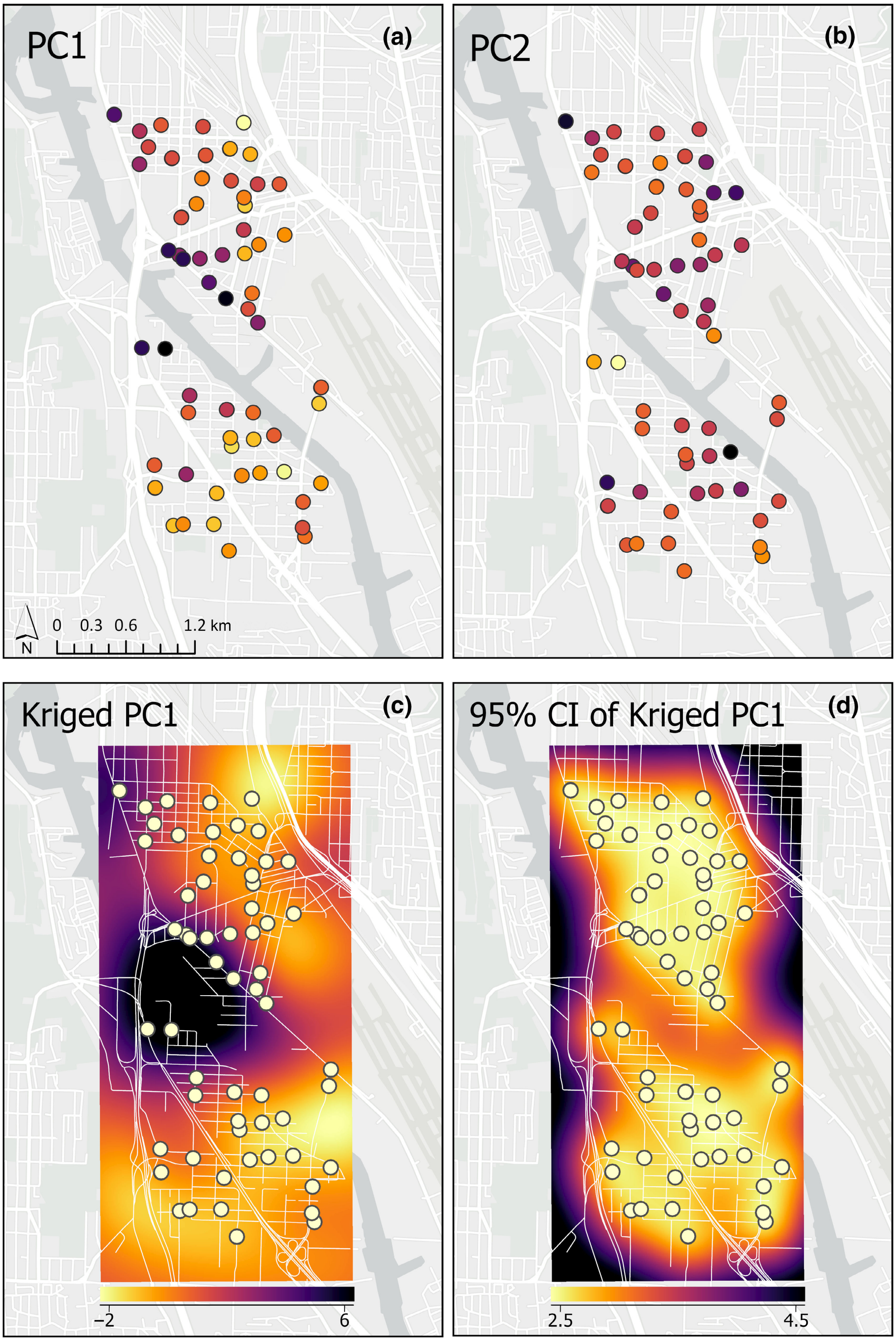


FIGURE 5 Maps of gradients in priority metals based on the similarity of elemental composition among moss sample sites. Each point, representing one sample site, is colored by its relative axis scores (yellow = lowest to purple = highest) along the two major gradients detected by principal component analysis (PCA): PC1 (a) and PC2 (b). We used kriging to interpolate scores for the dominant gradient PC1 (c). Confidence intervals for kriged PC1 scores varied across the study area (d), showing the uncertainty of interpolated values was highest at the edges of the sampled area.

with local government and community organizations. Given racial inequities and health disparities in the DV, the timeliness of these near-term actions is especially important, and green infrastructure offers many immediate co-benefits. The implementation of mitigation strategies is also helping foster trust among the networks of project partners, critical for collaborative resource planning, and management (Coleman & Stern, 2018).

3. *Follow-up air monitoring*: Our findings equipped community partners with new knowledge about pollutant distributions at the neighborhood scale. This helped community leaders advocate for a follow-up air monitoring campaign, in partnership with regulatory agencies (USEPA and PSCAA), to measure heavy metals in 2022. The campaign, sponsored by PSCAA, will deploy air monitoring instruments in locations selected by community partners based on local knowledge and the moss maps in this article (Figures 3 and 5; Appendix S2: Figure S2). Results will help determine whether metals detected in moss represent air concentrations with potential human health consequences. This critical question that will shape all subsequent steps in the partners' heavy metals investigation.

Synthesis and recommendations for follow-up air monitoring

After reviewing our results along with preexisting air modeling and monitoring data for the DV, we hypothesized that coarse particulates ($PM_{2.5-10}$) may be important, overlooked carriers of arsenic and other heavy metals in the DV. First, most monitors measure $PM_{2.5}$ only, including the local site "DW," which may explain why arsenic was not detected there. By contrast, moss tissues accumulate heavy metals within the broader PM_{10} size range (Adamo et al., 2008; Mariet et al., 2011; Massimi et al., 2019; Tretiach et al., 2011). Second, like the hotspots depicted in our maps (e.g., Figure 5), deposition of coarse particles is acute (i.e., concentrations vary widely across small areas) compared to the more gradual, regional-scale patterns of $PM_{2.5}$ (Massimi et al., 2019; Pakbin et al., 2010; Zhang et al., 2014). Finally, as discussed previously, airborne soil and dust (i.e., the main constituents of coarse particles; Watson & Chow, 2000) clearly influenced the elemental signatures of moss samples and correlated closely with arsenic levels, a major known contaminant of local MCTA and DV Superfund sites.

To test our hypothesis, the follow-up air monitoring campaign will focus on measuring priority metals in PM_{10}. Seattle's only PM_{10} monitor is the BH NATTs site, and a "reference" monitor that by design would not capture local patterns (Goswami et al., 2002) in the DV where periodic stagnation events trap local pollution (Roberts et al., 1975; Su et al., 2008). Even so, it is notable that in PM_{10} measured at BH, arsenic, cadmium, and chromium (as hexavalent chromium; Cr IV) rank among the top 12 HAPs with the highest potential cancer risk (PSCAA, 2018, 2019). Our emphasis on needing to monitor local PM_{10} is underscored by prior studies showing significantly much higher arsenic, cadmium, and chromium in Georgetown versus BH in measurements of TSP and deposition flux (King County, 2015; PSCAA and Washington State Department of Ecology, 2003).

Study limitations

We used a community science approach emphasizing the participation of youth and other community members, which required coordinating several groups with different time constraints. This led to three compromises in study design. First, fieldwork spanned 3 weeks and a flash thunderstorm that appeared to affect the study objective of comparing youth versus expert resamples (albeit not very importantly from a statistical perspective). Best practices for emphasizing spatial variability, however, are a brief (~3 days) sampling window with consistent weather conditions. Second, we sampled in summer when lead partners were active, which was not ideal for comparing with reference datasets collected in winter. Third, we sampled many street trees due to difficulty accessing interior trees on private lots, which is notable because particle deposition at roadside trees may be higher than trees short distances away (e.g., 100 m; Pant & Harrison, 2013). Nonetheless, we found strong and consistent geographic patterns of priority metals that helped partners prioritize and plan next steps with confidence—as was our goal for using moss as an inexpensive, first-pass screening tool.

CONCLUSIONS

As is common in urban neighborhoods, stakeholders in this study initially had few "on-the-ground" measurements for evaluating the predominance and spatial distributions of heavy metals. Due to limited capacities for conventional air monitoring, supplemental datasets from low-cost sensors, such as bioindicators, may be greatly beneficial in complex airsheds like the DV where industrial and residential land commingle; on a per-site basis, bioindicator data are orders of magnitude less expensive. As part of an ongoing collaboration among many community, agency, and university partners, our study of bioindicators significantly catalyzed and advanced efforts to address longstanding environmental justice challenges, enabling new contributions to community-led problem solving related to air quality and health in the DV. Our main findings—that youth can collect high-quality moss data; that priority metals in DV moss are relatively high versus reference datasets; that there are hotspots potentially warranting further investigation; and that PM_{10} may be an important local carrier of metals we know little about—helped the partnership steer finite resources toward effective community actions. In addition to these main findings, our collaborative process built invaluable trust, social capital, and capacity among community and noncommunity research partners, serving as an important example of how community science partnerships and bioindicators can guide environmental health and justice work.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Jovan et al., 2022) are available from Dryad: https://doi.org/10.5061/dryad.tqjq2bw1p.

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