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Lead-sheathed telecom cables and historic leaded gasoline emissions substantially raise environmental lead levels in Portland, Oregon

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We conducted a high-resolution study of lead in an urban moss, *Orthotrichum lyellii*, to better understand lead distributions and sources in Portland, Oregon (United States). The outdoor lead landscape is found to be heterogenous, with lead concentrations varying with age of neighborhood: on average 8.3× and 19× the rural background in newer (≥1948) and older neighborhoods (≤1915), respectively. This study finds leaded gasoline to be a pervasive and persistent lead source, decades after the complete phase out of leaded gasoline use by on-road vehicles. The highest lead levels, up to 590× the rural background, are found in older residential neighborhoods where relic lead-sheathed telecommunication cables were identified. Leaching of lead from these cables is thought to be responsible for elevated lead in older residential neighborhoods in cities across the country. Targeted research is needed to quantify the impact of these cables on lead exposures in affected communities.

Lead (Pb) is a highly toxic metal associated with adverse health effects including hypertension and cardiovascular disease[1], renal disease[2], neurodegenerative diseases like ALS[3], and decreased neurobehavioral-cognitive function[4]. Children are especially vulnerable as even low levels of lead in blood can adversely impact neurodevelopment[5] and cause lower IQ[6], poorer academic achievement[7], cognitive deficits[4], behavioral problems[8–10], and delayed puberty[11–13]. According to the Centers for Disease Control and Prevention (CDC) Advisory Committee on Childhood Lead Poisoning Prevention, no exposure limits are widely agreed upon as safe. Consequently, there is significant interest in identifying sources of lead pollution so that health risks can be mitigated.

Leaded gasoline, which was introduced for vehicular use in the 1920s, is a major source of lead pollution. Large-scale lead contamination associated with the use of leaded gasoline was first recognized and demonstrated by Clair Patterson and colleagues beginning in the 1960s[14–16]. Samples from Greenland and Antarctica demonstrate the far reach of these emissions[16–18]. Leaded gasoline use in on-road vehicles was banned in the United States (U.S.) in 1996 and ended worldwide in 2021 with the ban in Algeria. Leaded gasoline continues to be used in smaller piston-engine aircraft and some race cars.

Recent investigative reporting by the Wall Street Journal[19] revealed aerial lead-sheathed telecommunication cables as a potential lead source in modern cities. These lead cables were installed from the late 1800s until the 1960s in U.S. cities. As telecommunication has moved away from the use of lead-sheaths many of these cables have been removed. However, the Wall Street Journal[20] identified 450 aerial cable locations, many near schools, bus stops, parks, and homes, noting their search was likely to reflect only a small portion of the lead cables existing in the U.S. State and local government agencies and the broader public are thought to remain largely unaware of their presence.

For identifying pollution sources, lead levels can be measured and correlated spatially with emissions sources[21,22]. If the isotopic composition is also measured, then lead isotope "fingerprinting," can provide additional evidence for source. Lead has four stable isotopes, three (^{206}Pb, ^{207}Pb, and ^{208}Pb) are the stable end products of radioactive decay chains (^{238}U, ^{235}U, and ^{232}Th, respectively) and one non-radiogenic isotope (^{204}Pb). Lead ores from around the world have characteristic lead isotopic compositions that are fixed during mineral genesis[23], resulting in a lead isotopic fingerprint that is characteristic of the source. This isotopic fingerprint is maintained even after high-temperature processes such as metal smelting and refining. As a result, lead isotopic composition can be used to trace the source of lead emissions. For example, emissions from the combustion of leaded gasoline reflect the lead ores used to make the leaded gasoline additive, primarily tetraethyllead.

Biomonitors such as epiphytic moss and lichens have been used for decades to help assess the reach of metal emissions and changes in metal

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levels over time. These organisms lack roots, receiving all moisture, nutrients, and metals from the air, precipitation, and dust. As a result, their tissue concentrations reflect atmospheric levels and thus can be inexpensively measured to make temporal and spatial assessments of air quality, including areas poorly represented by air monitoring networks. Past research shows consistently strong correlations between lead levels in moss and atmospheric deposition[24].

Several studies have taken advantage of the fingerprinting ability of lead isotopes in moss and lichens for monitoring different pollution sources in urban environments[25–31]. However, these previous studies sampled at relatively low spatial resolution. Low-resolution sampling schemes will not capture the variation in lead levels or sources present in complex urban landscapes, making it difficult to identify localized sources of pollution. Such localized sources can only be reliably discovered using high-resolution sampling. For example, high-resolution sampling of moss uncovered stain glass manufacturers as a source of elevated cadmium levels in Portland. This was completely missed by regulators, prior to the investigation, and unknown to residents[22]. To our knowledge, there have been no high-resolution isotopic studies of lead pollution in cities using air monitors or biomonitors.

The goal of this study was to identify modern and persistent legacy lead sources in the large urban center Portland, Oregon (U.S.) including an investigation of the impact of relic lead-sheathed telecommunication cables. Lead remains an important contaminant in the city with a heterogenous presence made apparent by high-resolution moss sampling conducted in 2013[32]. Here we present the first analysis of the lead concentrations from that dataset ($n = 347$) and measurements of lead isotopes for a subsample of that collection ($n = 75$). Targeted sampling of Portland neighborhoods with lead-sheathed telecommunication cables was carried out in 2023 ($n = 38$) and used to evaluate their impact on local lead levels. These results were contextualized by comparisons with regional rural moss samples ($n = 11$) and archival moss and lichen samples ($n = 6$), which provide insights into modern background and historical lead levels and lead sources in the city. This paper presents the first high-resolution study of lead levels and isotope ratios in moss from an urban area demonstrating what can be gained from using cost-effective bioindicators in air quality investigations.

Results

To assess the distribution of lead pollution, moss samples were collected across Portland (2013 and 2023) and in nearby rural areas (2017), as illustrated in Fig. 1. These samples were analyzed for lead concentrations and isotopic compositions. Archival moss and lichen samples collected in and near Portland (Fig. 1) during the period of leaded gasoline use were also analyzed. A summary of the corresponding lead concentrations and $^{206}Pb/^{207}Pb$ and $^{208}Pb/^{207}Pb$ ratios is given in Supplementary Data 1. Lead concentrations and isotope ratios for individual moss and lichen samples are reported in Supplementary Data 2.

Portland lead levels and isotopic compositions

The lead concentrations of the 2013 Portland moss samples have a geometric mean of 5.42 ppm ($n = 347$), 11.7× higher than the background measured in rural moss (0.463 ppm, $n = 11$). The highest lead concentration sample of the 2013 Portland collection, 129 ppm, is 279× the rural background. Re-collection of moss in 2023 from previously sampled locations revealed sustained elevated lead concentrations, with concentrations as high as 271 ppm, or 586× the rural background. This is almost 2× the maximum lead concentration of archival Portland moss (142 ppm) collected during the peak of leaded gasoline use. The lowest lead concentration Portland sample, 1.03 ppm, is approximately 2× the rural background.

Moss samples from rural areas near Portland have an average $^{206}Pb/^{207}Pb$ isotope ratio of 1.1804, with a relatively small range of 0.0086. This is consistent with the lead isotopic signature of leaded gasoline[30,33–35], as well as archival Portland moss and lichen samples collected during the period of leaded gasoline use (which have $^{206}Pb/^{207}Pb$ ratios ranging from 1.1635 to 1.1838) (Supplementary Data 1). In contrast, the 2013 Portland moss samples have $^{206}Pb/^{207}Pb$ ratios ranging from 1.1165 to 1.2826, spanning a range of isotope ratios almost 20× larger than that of the rural moss samples. An even wider spread of $^{206}Pb/^{207}Pb$ ratios is found for the 2023 Portland samples, which range from 1.1147 to 1.3106. The large ranges in lead concentrations and isotopic compositions observed in Portland suggest a highly complicated lead landscape.

Effect of neighborhood age

To explore the reasons for the high variation in lead levels, we first examined the effect of neighborhood age. Figure 2a shows a histogram of measured lead levels where neighborhood annexation decade is identified using different colors. There is a clear trend of higher lead levels in older neighborhoods. To quantitatively examine the effect of neighborhood age, the data were divided into three groups, before 1915, after 1948, and the Portland outskirts (which had annexation dates after 1970). Note no samples were taken from locations with annexation dates between 1916 and 1947 reflecting a gap in the expansion of Portland through annexations of neighborhoods during this period. This gap was chosen as the dividing line between older and newer neighborhoods. The resulting data are shown in

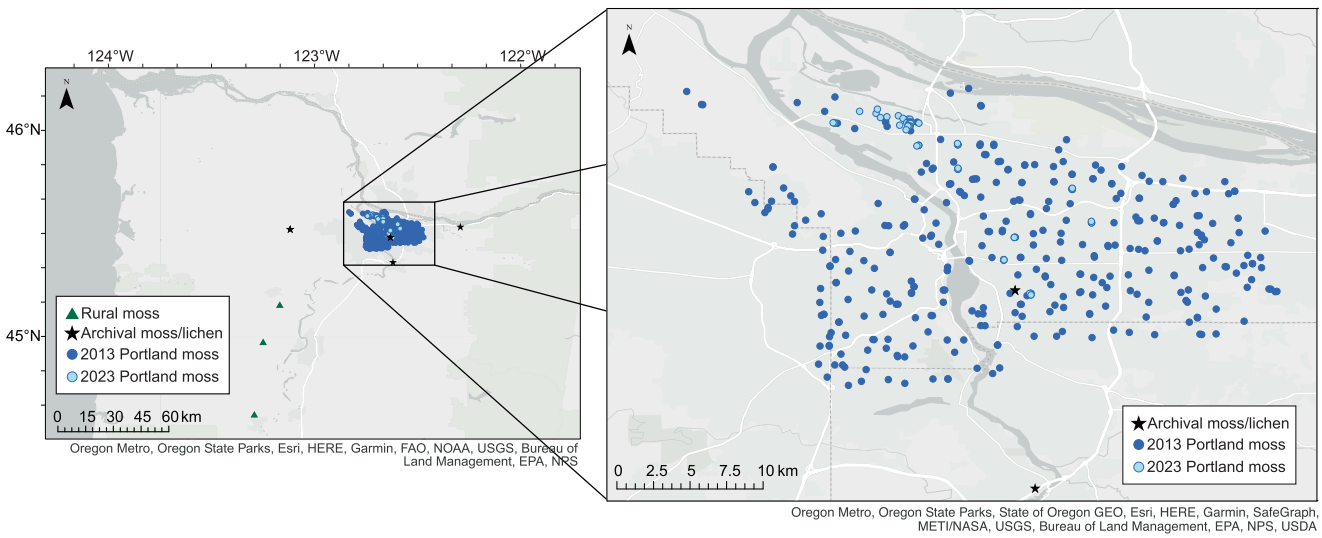

Fig. 1 | Moss and lichen collection locations for Portland and rural Oregon (U.S.). Left, a map of northwest Oregon with rural samples identified as green triangles, archival moss and lichen identified as black stars, and Portland moss identified as dark blue (2013) and light blue (2023) circles. Right, a map of Portland and the surrounding area showing the distribution of the archival, 2013, and 2023 moss and lichen samples across the city.

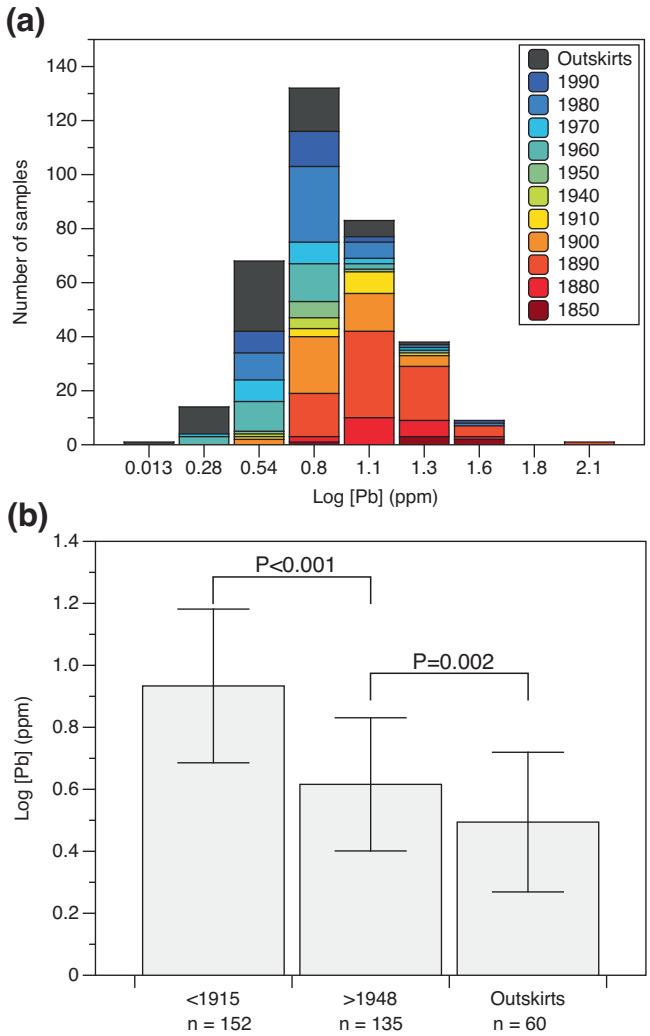

Fig. 2 | Effect of neighborhood age on lead concentrations in 2013 Portland moss. **a** Histogram of the distribution of lead concentrations for 2013 Portland moss by neighborhood annexation decade. Locations outside of Portland including suburbs are identified as the outskirts. **b** Bar graph of the mean (+/−1 SD) log lead concentrations (ppm) for each of the 2013 Portland sample groups. *P* values determined using Tukey's post hoc test for multiple comparisons are shown.

Fig. 2b. Moss from locations with annexation dates prior to 1915 have a geometric mean lead concentration of 8.58 ppm (n = 152), 2–3× higher than the geometric means of moss from locations with annexation dates 1948 and later (4.13 ppm, n = 135) and the Portland outskirts (3.12 ppm, n = 60). The geometric mean of moss from locations with annexation dates 1948 and later is 1.3× that of the Portland outskirts. A one-way ANOVA revealed a statistically significant effect of neighborhood age on lead levels ($F(2,344) = 107$, $P < 0.001$). Tukey's post hoc test for multiple comparisons showed that lead levels are significantly different for all pairs ($P \leq 0.002$).

While neighborhood age may in part explain the variability in lead levels across Portland, it does not tell the whole story. Even among locations with the same annexation date, wide variation in lead levels was observed. This is especially striking when comparing samples collected in close proximity to each other. For example, the lead concentration of LH 1-69, the 2013 Portland sample with the highest lead concentration, is 18× that of LH 1-72, collected just 400 m away (Supplementary Data 2). Two-to-three-fold differences in lead levels were observed for several of the field pairs located 30–100 m apart (Fig. 3a).

We also examined the relationship between neighborhood age and lead isotopic compositions (Fig. 4a). Samples from locations with annexation dates before 1915 exhibit a range in $^{206}Pb/^{207}Pb$ ratios 5.6× that of samples from locations with annexation dates after 1948 (Fig. 4b; Supplementary Data 1). The most extreme lead isotopic ratios accompany the highest lead concentrations and are exhibited by moss from the oldest Portland neighborhoods (Fig. 4a). This is the case for the samples with both the most radiogenic isotopic compositions ($^{206}Pb/^{207}Pb$ as high as 1.3106) and the least radiogenic compositions ($^{206}Pb/^{207}Pb$ as low as 1.1147). These isotope ratios are outside of the range observed for leaded gasoline[34,35], suggesting an additional source of lead pollution in older Portland neighborhoods. In some cases, lead isotope ratios varied widely, even over short distances. For example, field pair LH 2-60 and LH 2-61 are located 30 m apart and have a difference in $^{206}Pb/^{207}Pb$ ratio of almost 0.08 (Fig. 3b), equivalent to 50% of the total variation observed for all 2013 Portland samples. This large difference between samples collected in close proximity suggests that there are localized sources of lead pollution in these older neighborhoods.

Effect of lead-sheathed telecommunication cables

To assess whether pollution from lead-sheathed telecommunication cables could explain the high variation in lead levels and isotope ratios across Portland, the 2013 data were re-examined. Sixteen of the sampling sites from 2013, including five field pairs located 0–100 m from the other site, were found to have lead-sheathed telecommunication cables present (Supplementary Data 2). For nine of the sites, the lead cables were identified in the most recent Google Street View image and confirmed in person. For four of the sites (LH 2-60, LH 2-61, LH 3-18, LH 3-19), the lead cables have been removed and were identified in older Google Street View images. For six sites including one field duplicate (i.e., collected 0 m from the other site) the lead cables are positioned on the same side of the street, within 1 m of the sampling location. For the remaining 10 samples, lead cables are positioned 7–100 m away from the sampling location, on the opposite side of the street or on an adjacent street (Supplementary Data 2). These sites were distributed across 11 neighborhoods with annexation dates between 1891 and 1906.

The geometric mean of 17.6 ppm lead for moss from these 16 locations is more than 2× that of 2013 Portland locations with annexation dates before 1915 without lead cables (7.88 ppm) and 38× higher than that of the rural background (Supplementary Data 1). A two-sided t-test revealed a significant difference between the lead levels of moss from older neighborhoods with and without lead cables ($t(17) = 4.20$, $P < 0.001$). The highest lead concentrations, up to 129 ppm, are found in samples collected within 1 m of a lead cable.

Targeted sampling in 2023 allowed further investigation of the impact of lead-sheathed telecommunication cables on lead levels (Fig. 5a). Moss from locations with lead cables have a geometric mean lead concentration of 15.3 ppm, 5.56× higher than that of moss from locations without lead cables (2.74 ppm) (Fig. 5a, Supplementary Data 1). The maximum lead concentration of 271 ppm is approximately 100× higher. For both the 2013 and 2023 Portland moss samples, the highest lead concentrations and most extreme lead isotope compositions were measured in samples from locations <1 m from lead cables (Figs. 4 and 5). However, contributions of lead leached from these lead cables are apparent in moss 6–100 m away (Fig. 5b).

To examine how lead pollution originating from the cables persists over time, we compared the results for two neighborhoods (Sunnyside and Woodstock) that were sampled in 2013 (LH 2-61 and LH 3-18) and 2023 (ASP-10 and ASP-14). For these locations, the lead cables were removed around the time of the first sampling in 2013. Re-collection at these sites in 2023 revealed sustained elevated lead levels and isotopic compositions that differ from the Portland mean 10 years later (Supplementary Data 2). Smaller contributions of lead from the lead cables can be detected in moss growing on a tree planted ≥7 years after the lead cable was removed (Woodstock: ASP-13) (Supplementary Data 2).

Identification of lead-sheathed telecommunication cables is limited here by the Google Street View images available. For much of Portland, images are available dating back to 2007. However, for some sites, only newer images are available. It is probable that lead cables were removed from

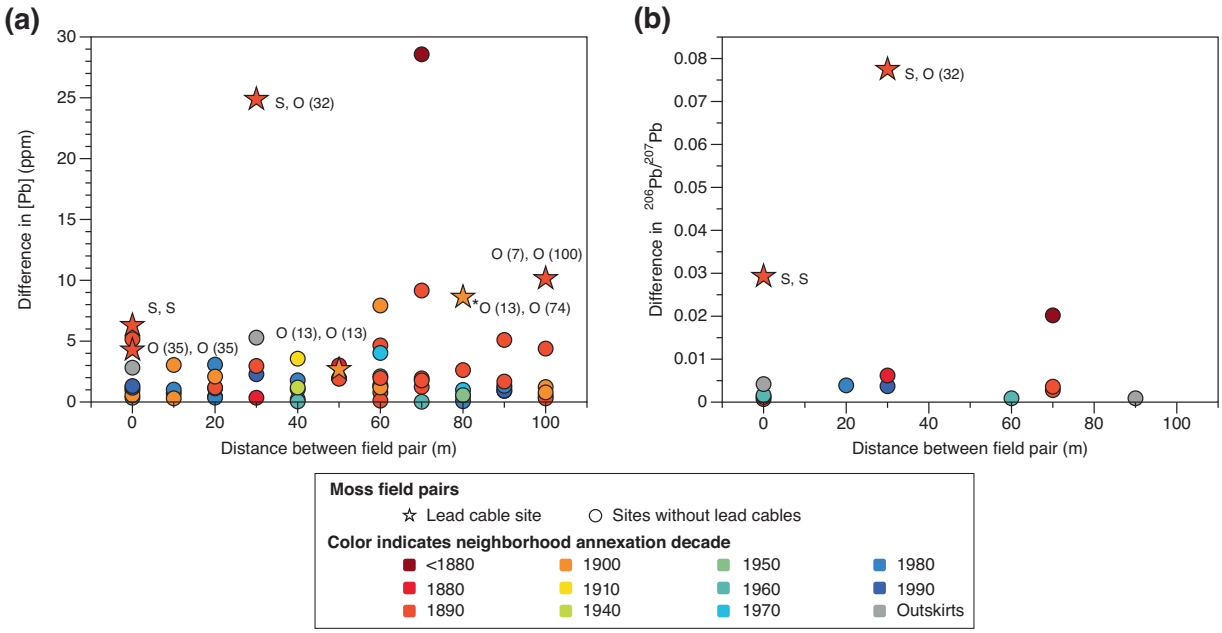

Fig. 3 | Differences in lead concentrations and isotope ratios for 2013 Portland moss field pairs. Plots of **a** the difference in lead concentration (ppm) versus the distance (m) between the two sampling locations for all 70 field pairs and **b** the difference in $^{206}Pb/^{207}Pb$ ratios versus the distance (m) between the two sampling locations for the 14 field pairs included in the lead isotope study. Samples are colored based on the annexation decade of the sampling location. Stars are used to indicate sites with lead cables. For those sites, S indicates that the sample was taken from the same side of the street (<1 m away) and O on the opposite side of the street. An approximate distance (m) from the lead cables is given in parentheses for the latter. An asterisk is used to identify the field pair, LH 3-21 and LH 3-22, in (**a**), collected at the suspected location of former lead cables. Error bars on lead concentrations are excluded for figure clarity but are reported in Supplementary Data 2. Uncertainty on $^{206}Pb/^{207}Pb$ ratios is smaller than the symbol size.

additional sites included in this study prior to the oldest Google Street View images available. In these cases, lead leached from lead cables may be suggested by the age of the neighborhood, the presence of old wooden utility poles, elevated lead concentrations near the path of overhead cables, large differences between the lead concentrations and isotopic compositions of samples collected in close proximity, and lead isotopic compositions consistent with lead cables. As examples, lead in two samples included in the lead isotope study (LH 1-45 and LH 2-76) is suspected to result from the historical presence of lead cables based on the age of the neighborhoods (annexed in the 1880s), elevated lead concentrations (17.0 and 12.9 ppm, respectively), and lead isotopic compositions consistent with those of moss from other sites in Portland identified as having lead cables (Fig. 4a) (Supplementary Data 2). An additional site included in the lead concentration study is suspected to be impacted by historical lead cables based on the three-fold difference in the lead concentrations of a field pair located 80 m apart (LH 3-21 and LH 3-22) (Fig. 3a).

Discussion

Leaded gasoline's legacy

The lead isotopic compositions of moss from Portland sites (excluding those with lead cables) are consistent with that of leaded gasoline used in Portland (this study) and California[30,33–37] (Fig. 6). This suggests that the resuspension of soil and dust contaminated with lead from the historical use of leaded gasoline is the dominant lead source for most Portland mosses (Fig. 6). Laidlaw et al.[38] reported the resuspension of soil as a major source of atmospheric lead in cities, finding both the soil lead burden and traffic turbulence to play roles in measured soil lead levels. While a similar high-resolution study for moss and lichens does not exist for other urban areas, previous studies employing high-resolution soil sampling report alarming lead levels at some locations that would be missed by sparse sampling schemes[39–42]. They similarly attributed elevated lead levels in streetside soils primarily to legacy lead emissions from leaded gasoline[39–42]. Evidence for the persistence of lead from historical leaded gasoline in lichens can also be seen for San Francisco (2000 and 2006[30]) and Seattle (2016–2017[29]). Lichens from western Canada, sampled in 2003, had similar lead isotopic compositions, with a larger percentage of samples falling toward the unradiogenic end of the range, suggesting larger contributions from a relatively unradiogenic lead source, probably Sullivan lead ore, used to make the lead additive for leaded gasoline in Canada[25]. Other studies have similarly reported the persistence of lead from historical industrial and leaded gasoline emissions in modern environments, e.g., on the U.S. west coast, in the San Francisco Bay estuary system[37,43], Sacramento River[44], Lake Tahoe[45], and in the Los Angeles area[46], and in Metz, NE France[27,28], Sydney, Australia[31], and London, UK[47].

Lead-sheathed telecommunication cables

High-resolution sampling of moss across Portland has revealed the heterogenous nature of lead burdens across the city[32] (Fig. 4). The legacy of leaded gasoline contributes to a largely homogeneous lead isotope signature observed in moss collected across Portland. However, this lead isotope signature can be overwritten by significant inputs of local lead where they exist. The highest lead concentrations and the least and most radiogenic lead isotopic compositions (lowest and highest $^{206}Pb/^{207}Pb$ ratios) of the 2013 (Fig. 4) and 2023 (Fig. 5) Portland samples are attributed to lead-sheathed telecommunication cables identified at the sites. Leaching of lead from these cables contaminates local vegetation, including moss, and soils (A.E.S., S.J., C.M., paper in prep). Lead-contaminated soil and dust is thought to be mobilized by wind, traffic, landscaping, and other activities and deposited on the moss. This contaminated soil remains a local source of lead at these sites after the lead telecommunication cables have been removed. Local heterogeneity in moss lead levels and isotopic compositions is thought to reflect differences among the microenvironments of each moss sampling location based on factors such as thickness of the tree canopy, distance to the soil, and local ground cover.

While this study was limited to moss, preliminary investigation of soils at sites under investigation here has revealed lead concentrations of 134 to 353 ppm ($n = 5$) (A.E.S., S.J., C.M., paper in prep). An investigation by the U.S. Environmental Protection Agency (EPA) found soil lead

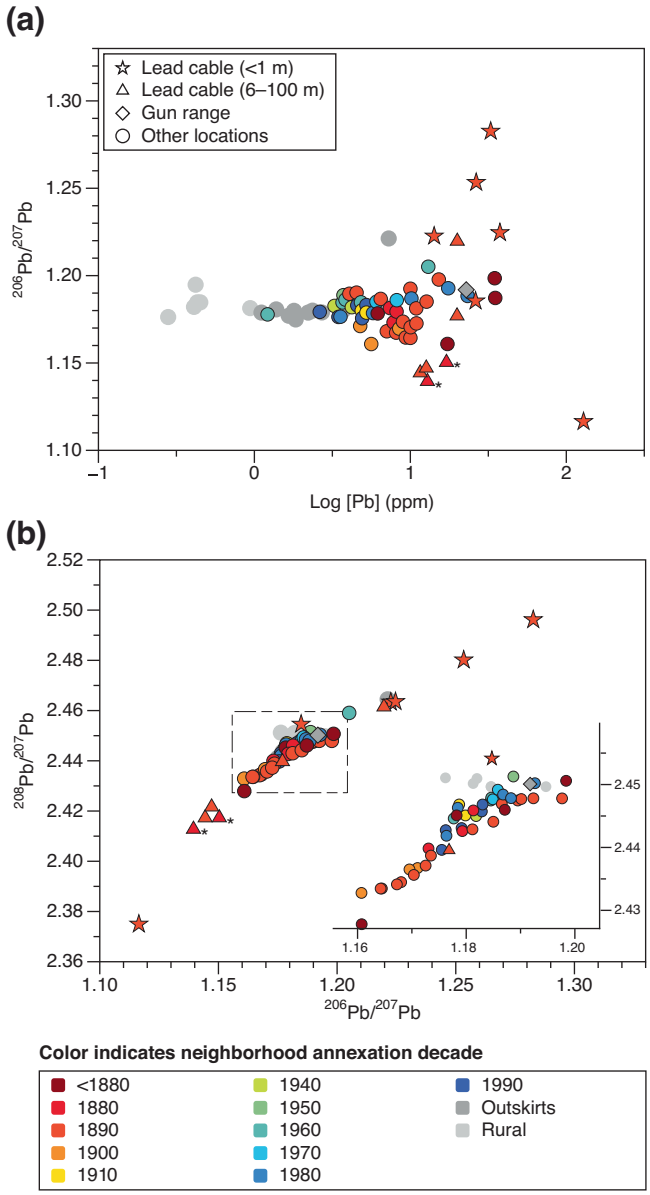

Fig. 4 | Effect of neighborhood age on lead isotope ratios in 2013 Portland moss. Plots of **a** $^{206}Pb/^{207}Pb$ ratios versus the log lead concentration (ppm) and **b** $^{208}Pb/^{207}Pb$ versus $^{206}Pb/^{207}Pb$ ratios for the 2013 Portland and rural moss samples, where color identifies the annexation decade for the collection locations in Portland. Urban locations outside of Portland are identified as the Portland outskirts. Error bars on lead concentrations are excluded for figure clarity but are reported in Supplementary Data 2. Uncertainty on $^{206}Pb/^{207}Pb$ ratios is smaller than the symbol size.

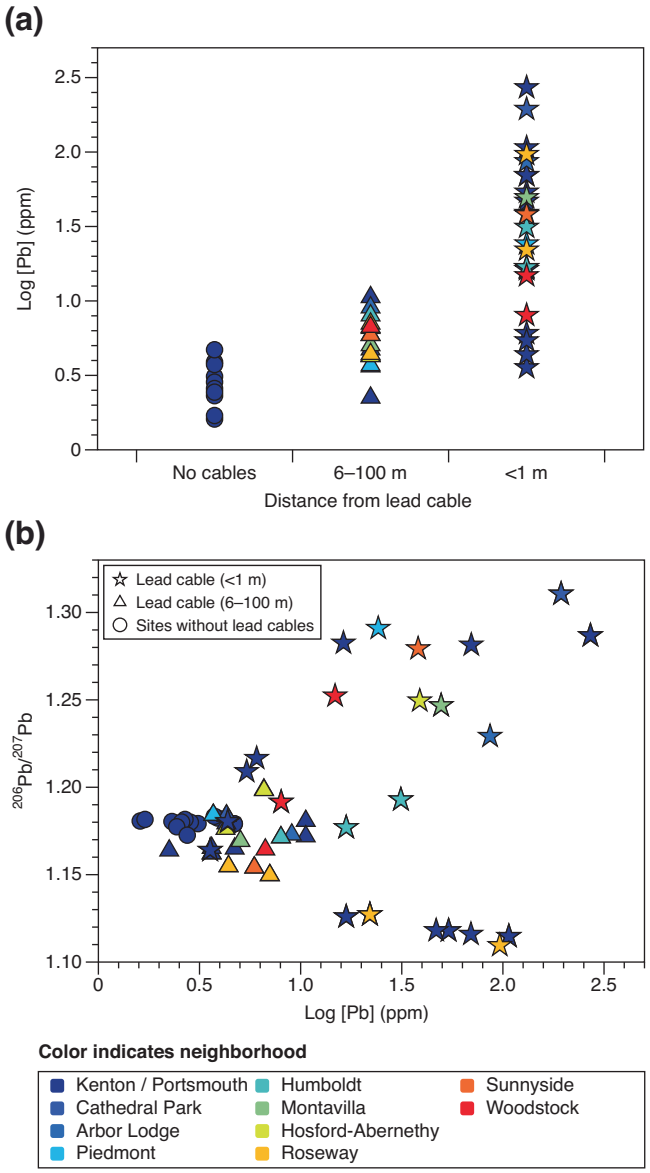

Fig. 5 | Impact of lead cables on lead concentrations and isotope ratios for 2023 Portland moss. Plots of **a** log lead concentration (ppm) for samples grouped by distance to the nearest lead-sheathed telecommunication cable, and **b** $^{206}Pb/^{207}Pb$ ratios versus log lead concentration (ppm) for the 2023 Portland moss samples. Color identifies the Portland neighborhood. Annexation decade for the sampled locations is between 1891 and 1906. Error bars on lead concentrations are excluded for figure clarity but are reported in Supplementary Data 2. Uncertainty on $^{206}Pb/^{207}Pb$ ratios is smaller than the symbol size.

concentrations as high as 1400 and 3400 ppm, with geometric means of 251 ppm ($n = 31$) and 347 ppm ($n = 192$), under lead cables at Wall Street Journal identified sites in California and Coal Center, Pennsylvania (response.epa.gov/CalandCoal) and West Orange, New Jersey (response.epa.gov/leadcablesNJ), respectively. The EPA recommended screening level for lead-contaminated soils in residential areas is 200 and 100 ppm when additional sources of lead such as in air and water are identified. For topsoils at both EPA study sites ($n = 96$), 73% of samples were over the 200 ppm lead screening level and 91% of samples were over the 100 ppm lead screening level. Caravanos et al.[48] report similarly elevated soil lead levels below aerial lead cables at an additional Wall Street Journal identified site in New York. They confirm the primary contamination point is directly under aerial lead cables based on observed decreases in soil lead levels, on average 35%, within a few feet of the cables[48].

Targeted sampling near lead-sheathed telecommunication cables in 2023, including broad sampling in the Kenton/Portsmouth neighborhood, demonstrates that these cables are consistently associated with elevated lead concentrations and lead isotopic compositions characteristic of the cables (Fig. 5) and distinct from that of leaded gasoline (Fig. 6). The highest lead levels and most extreme isotopic compositions are found in moss sampled from <1 m from a lead-sheathed telecommunication cable (Fig. 5). Elevated lead levels and isotopic compositions representative of contributions from local lead cables are identified in moss sampled 6–100 m away (Fig. 5). Lead leached into soils from lead cables not detected in this study may also be contributing lead at these sites. Elevated lead and characteristic lead isotopic compositions are found to persist in moss 10 years following lead cable removal (Sunnyside: LH 2-61, ASP-10; Woodstock: LH 3-18, ASP-14; Supplementary Data 2). This is thought to reflect the persistence of lead in

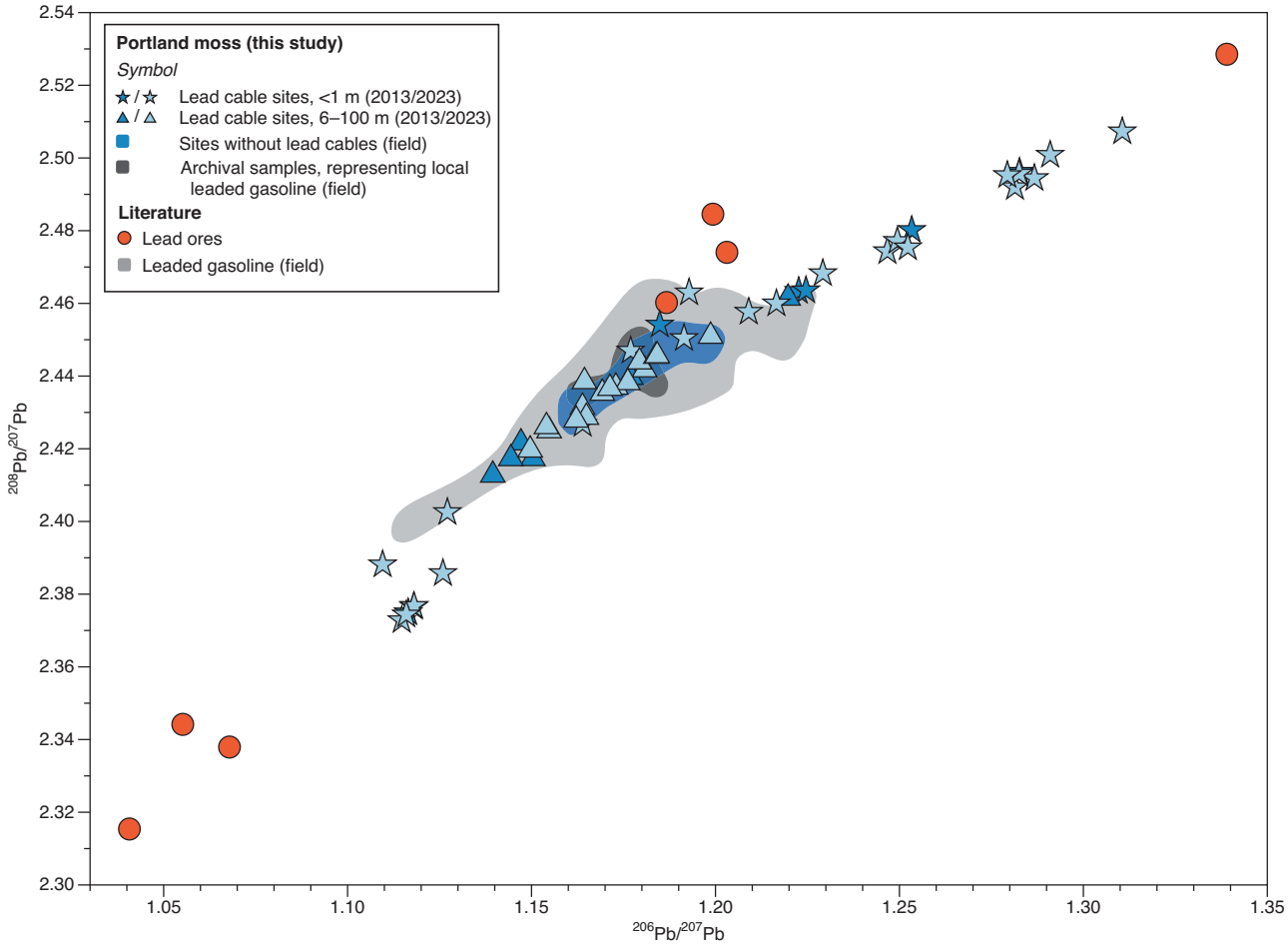

Fig. 6 | Lead isotopic compositions of Portland moss compared with lead ores and leaded gasoline. A plot of $^{208}Pb/^{207}Pb$ versus $^{206}Pb/^{207}Pb$ ratios for Portland moss plotted with lead ores (red circles) and leaded gasoline (gray field). The charcoal field represents the lead isotopic compositions of archival Portland moss and lichen samples from the period of leaded gasoline use. The blue field represents the lead isotopic compositions of the primary cluster of 2013 and 2023 Portland moss sampled from locations without lead-sheathed telecommunication cables. Samples from locations with lead cables (Supplementary Data 2) are identified with stars and triangles. Lead ores are from, in order of increasing $^{206}Pb/^{207}Pb$ ratios, Broken Hill (Australia)[49], Coeur d'Allene (U.S.)[50], Sullivan (Canada)[49], Santa Eulalia (Mexico)[49], Cerro de Pasco (Peru)[49], Parrall (Mexico)[49], and Southeast Missouri (U.S.)[49]. The leaded gasoline field is drawn from measurements of leaded gasoline, aerosols, contaminated sediments, and archival lichens[30,33–37]. Uncertainty on $^{206}Pb/^{207}Pb$ and $^{208}Pb/^{207}Pb$ ratios is smaller than the symbol size.

local soils and dust (A.E.S., S.J., C.M., paper in prep). Variability in the lead isotope signature of the lead cables reflects changes in the major global sources of lead ores used in their production (Fig. 6). This includes characteristically unradiogenic lead ores mined from the Broken Hill (Australia)[49], Coeur d'Alene (U.S.)[50], and Sullivan (Canada)[49] mining regions and radiogenic lead ores from SE Missouri mining regions (U.S.)[49] (Fig. 6).

Other sources of urban lead variability

Lead emissions from other point sources are expected to contribute to elevated lead levels where they exist. For example, in SE Portland, the elevated lead concentration of 22.8 ppm of moss sample LH 4-6E is attributed to lead emissions from the use of lead shot at the nearby Portland Gun Club (Fig. 4a). It's also expected that in older residential neighborhoods exterior lead-based paint is a source of lead. However, lead-based paint is not expected to play prominently in this study as moss sampling in residential neighborhoods was limited to street trees. Previous studies of lead in urban soils have reported significantly higher lead levels attributable to lead-based paint in soils collected next to the foundations of older homes or in the yards as opposed to streetside[39,40].

Conclusions

This study presents lead concentrations and isotope ratios for moss samples from the large urban center, Portland, Oregon (U.S.). The highest lead concentrations are found in the oldest neighborhoods of Portland, including in both the city center and in residential neighborhoods. The lead isotopic compositions of moss from Portland and the surrounding area evidence legacy leaded gasoline emissions as the primary source of lead, decades after its discontinued use. Relic lead-sheathed telecommunication cables were identified as responsible for the highest lead levels and the most extreme (both least and most radiogenic) lead isotopic compositions of the 2013 collection. Targeted sampling in relation to lead cables in 2023 demonstrates elevated lead consistently accompanies these cables and provides evidence that relic lead-sheathed telecommunication cables are releasing lead into residential neighborhoods. While the lead isotope signature of the lead cables is variable among Portland neighborhoods the difference between the lead isotope signature of any given cable and that of legacy leaded gasoline emissions allows the reach of lead from lead-sheathed telecommunication cables to be assessed. The environmental burden of lead will continue to increase near these sources until they are removed. Further, this lead is expected to be persistent in urban landscapes, remaining present outside of removal and disposal of contaminated soils.

Methods

Site description and sample collection

Portland is the largest city in Oregon and the 6th largest city on the U.S. west coast with a metro area population of ~2.2 million. This study includes an

analysis of lead levels and isotopic compositions of (1) moss samples collected from Portland in 2013, (2) moss samples collected 10 years later in 2023 for proximity to lead-sheathed telecommunication cables, (3) archival moss and lichen samples, and (4) rural moss samples.

Moss sampling protocol

In 2013 a random sampling in grids approach was used to identify moss sampling locations across Portland. Details are provided by Donovan et al.[22] and Gatziolis et al.[32]. In brief, samples were located on a 1 km^2 grid extending 1 km beyond the city borders. A randomly selected residential address in each grid cell was chosen as the sampling location. The acrocarpous epiphytic moss species *Orthotrichum lyellii* was collected from several locations on a single hardwood tree at least 1 m off the ground to reduce the influence of road spray and pet urine. This species was selected for its presence across Portland, even in more polluted areas, and for ease of sampling. This species grows in tufts making it relatively easy to separate healthy more recent growth from rhizoids and debris accumulated at the tuft base. Over 50% of samples came from street trees. Samples ($n = 347$; Fig. 1) were analyzed for 22 elements. Metals in these moss samples are thought to represent accumulation over several months to a maximum of three years[32]. Results for lead revealed gradients and hotspots of lead concentrations across the city[32]. To capture variability in metal concentrations across short distances, 70 field pairs were collected: 12 from the same location (identified by the suffix r0) and 58 from 10–100 m of the randomly selected sites (identified by the suffix r+ the distance in m, e.g., r10 for 10 m) (Supplementary Data 2).

In 2023 (10 years later) targeted sampling was used to assess the impacts of lead-sheathed telecommunication cables on local lead levels. The identification of these lead cables in neighborhoods sampled in 2013 is described below. The moss *O. lyellii* was collected from 10 of the 11 neighborhoods found to have these lead-sheathed telecommunication cables ($n = 38$; Fig. 1). In each neighborhood, moss was collected from the original sampling location (identified as a resample in Supplementary Data 2) and at least one other location. The second location was chosen such that for each neighborhood moss growing within 1 m of a lead cable and from 6 to 35 m of a lead cable is included in the study. In most cases, the latter is from the opposite side of a residential street 10–13 m from the lead-sheathed telecommunication cable. For the Arbor Lodge neighborhood, the lead-sheathed telecommunication cable runs along a wide busy road and so the moss collected from the opposite side of the street was 35 m away (LH 1-62, LH 1-63, and LH-7). For the Kenton/Portsmouth neighborhood more intensive sampling was conducted and included 17 locations with lead-sheathed telecommunication cables and 10 residential sampling locations away from lead-sheathed telecommunication cables (Fig. 1).

To assess the regional lead background, *O. lyellii* samples ($n = 11$) were collected from Baskett Slough National Wildlife Refuge (BSNWR)[51], Miller Woods Conservation Area (MWCA)[51], and McDonald Forest (Fig. 1). A regional background lead level was estimated based on the *O. lyellii* rural sites (Supplementary Data 2). The local historical gasoline lead isotopic composition was assessed using available archival moss and lichen samples ($n = 6$) obtained from the Portland State University Herbarium. These samples were collected in or close to Portland between 1959 to 1974 (Supplementary Data 2). Dried whole specimens were received and prepared similarly to other samples included in the study. Geographical coordinates were inferred from sampling location descriptions.

Lead isotope study

Moss samples from Portland analyzed for lead isotopes ($n = 70$) were selected from the city-wide collection ($n = 347$) sampled in 2013 (Fig. 1). We selected moss with the 10 highest and five lowest lead concentrations. We also randomly selected five samples where a field duplicate was collected at the same location immediately after the original sample (identified by the suffix 'r0' in the Sample collection site; Supplementary Data 2). The remaining samples were randomly selected from the whole dataset. If a randomly selected site had a field pair, we included both in the study (9 sites). In total 14 field pairs were included in the lead isotope study with sampling distances between 0 and 90 m between the pairs (Supplementary Data 2).

Lead isotope ratios were also measured in the 2023 Portland moss samples ($n = 45$), rural moss samples from BSNWR and MWCA ($n = 7$), and archival moss and lichen samples ($n = 6$) (Fig. 1). Rural moss samples from McDonald Forest were measured for lead concentrations only. Full procedural duplicates and replicated measurements are included in Supplementary Data 2.

Sample preparation for lead analysis

Foreign material, such as bark and other moss and lichen species, were removed from samples using gloved hands, titanium scissors, and tweezers in a laboratory. The *O. lyellii* samples were additionally trimmed to remove the base keeping only the upper 2/3 of the sample, selecting for the most recent growth[22]. Samples were then oven dried, ground, and homogenized. Samples were digested using ultrapure nitric and hydrofluoric acids and hydrogen peroxide. Sample lead was isolated for isotopic analysis by anion-exchange chromatography using the AG 1-X8 (100–200 mesh) resin (Bio-Rad Laboratories Inc.)[52].

Analytical methods

Experimental work was carried out in the Class 100 clean laboratory at the Keck Collaboratory, Oregon State University (OSU). Elemental analysis was carried out on the iCAP RQ inductively coupled plasma mass spectrometer (ICP-MS). Lead concentrations were quantified using external calibration curves. Indium (In) or rhenium (Re) was used as an internal standard. All solutions were prepared with 0.15 M HNO_3. Standard solutions used for element concentration determination were prepared from single-element solutions from High Purity Standards (U.S.) or Inorganic Ventures (U.S.).

Lead isotopic analysis for all samples was performed on the Nu Plasma (Nu Instruments, UK) multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) instruments Nu 023 and Nu 3D 015 (Keck Collaboratory, OSU). Lead analyses are comprised of 60 measurements. For the 2013 Portland moss samples, this was 3 blocks of 20 × 10 s integrations with a 30 s ESA deflected baseline before each block. Measurements of the remaining moss and lichen samples utilized 3 blocks of 20 × 5 s integrations with a 60 s measured zeros routine run approximately every six samples. Ion signal intensities were measured for masses 202–208. Samples were run following a sample-standard bracketing (SSB) measurement protocol. The NIST (U.S.) SRM 981 natural lead (isotopic) standard was used for monitoring analytical run instrument drift and normalization of all measured lead isotope ratios relative to the triple-spike values of Galer and Abouchami[53]. The isobaric Hg interference on ^{204}Pb was corrected by monitoring ^{202}Hg and assuming natural abundances, $^{202}Hg/^{204}Hg = 4.350$[54].

Analytical quality assurance and quality control

Lichen certified reference materials (CRM) BCR-482 (Institute for Reference Materials and Methods, Belgium) and IAEA-336 (International Atomic Energy Agency, Austria) were processed with each batch of samples and measured for lead concentration at OSU to ensure accurate results. Moss certified reference materials were not available. Recoveries for lead were 86–95% for 8 digestions of BCR-482 based on the certified value ($n = 10$) and 88–97% for 9 digestions of IAEA-336 based on the reported information value ($n = 23$) (Supplementary Data 3). Uncertainty on lead concentration measurements is estimated as 2× standard error, 25.4‰ and 24.8‰, based on repeat analysis of IAEA 336 ($n = 9$) and BCR-482 ($n = 11$), respectively (Supplementary Data 3).

These lichen reference materials were also measured for lead isotopic composition and compared to previously reported measurements for these reference materials in the case of BCR-482[27,28]. This is the first reported lead isotopic measurement of IAEA-336 to our knowledge. In addition, geological reference materials AGV-1, BCR-2, GSP-2, and RGM-1 (USGS) were measured for lead isotopic composition. Our measurements are consistent with previously reported values[55,56]. A summary of these values is provided in Supplementary Data 4.

Replicate measurements of lead isotope ratios were made for 33 samples (Supplementary Data 2). The analytical uncertainty of the data was estimated using 2× the mean absolute difference (MAD) precision[57] as ±0.01% for $^{206}Pb/^{204}Pb$, 0.01% for $^{207}Pb/^{204}Pb$, 0.02% for $^{208}Pb/^{204}Pb$, 0.009% for $^{206}Pb/^{207}Pb$, 0.009% for $^{208}Pb/^{206}Pb$, and 0.004% for $^{208}Pb/^{207}Pb$ (95% confidence) (Supplementary Data 5). For the average 2013 Portland moss sample lead isotopic composition this is ±0.0022 for $^{206}Pb/^{204}Pb$, 0.0018 for $^{207}Pb/^{204}Pb$, 0.0059 for $^{208}Pb/^{204}Pb$, 0.00010 for $^{206}Pb/^{207}Pb$, 0.00020 for $^{208}Pb/^{206}Pb$, and 0.00009 for $^{208}Pb/^{207}Pb$ (95% confidence) (Supplementary Data 5). The MAD precision was preferred over the root mean squared (RMS) precision in this case as it is less sensitive to outliers[57]. Both values are reported in Supplementary Data 5. Measurements of duplicate preps of the same sample were also performed and monitored for consistency (Supplementary Data 2).

Data presentation

For lead, the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{206}Pb/^{207}Pb$, $^{208}Pb/^{206}Pb$, and $^{208}Pb/^{207}Pb$ ratios are reported (Supplementary Data 2). Graphics without 204 are highlighted in the manuscript as these ratios are more consistently available in the literature. For samples measured more than once (identified as having a duplicate prep or replicate analysis in Supplementary Data 2) the first measurement is used in all figures and in the calculation of summary statistics (Supplementary Data 1).

To examine correlations between lead concentrations, isotope signatures, and the age of sampled neighborhoods, the annexation dates for sampling locations in Portland were identified (https://www.portland.gov/bps/documents/historical-annexations-city-portland) in ArcGIS Pro (Supplementary Data 2).

Data transformation

Graphs of the 2013 Portland moss lead concentration data indicate that the data are not from a normal distribution. A histogram shows that the lead concentration data are highly right skewed, with a majority of low values and a few high extremes. Descriptive statistics confirm this, with a mean (7.08 ppm) much higher than the median (4.99 ppm) and skewness and kurtosis statistics of 9.31 and 126. A $\log_{10}$ transformation yields a dataset that more closely conforms to a normal distribution, as shown by the histogram (Fig. 2a) and a quantile-quantile plot. The mean (0.734) is closer to the median (0.698), and the skewness and kurtosis statistics of 0.532 and 1.11 are much closer to zero. As a result, for lead concentrations, geometric means rather than arithmetic means are reported, and statistical t-tests, one-way ANOVA, and Tukey tests are performed on log-transformed data. All statistical tests were performed using JMP Pro 16.0.0.

Identification of lead-sheathed telecommunication cables

54% of the 2013 moss sampling sites ($n = 186$) were checked for the presence of old lead-sheathed telecommunication cables using the most recent images (typically from 2019 to 2022) from Google Street View. This analysis included all Portland sampling sites with annexation years occurring in the 1950s and earlier and those with lead isotope ratios outside the primary cluster observed for Portland. In-person verification was done for sites on streets identified as having lead-sheathed telecommunication cables. Older images (as old as 2007) were analyzed, as available for sites, not found to have lead cables in the most recent images but suspected to be impacted by lead cables given elevated lead levels and/or lead isotopic compositions inconsistent with historic leaded gasoline emissions.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available in the Dryad data repository (https://doi.org/10.5061/dryad.1rn8pk12g)[58] and in the Supplementary Information.

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Author contributions
Alyssa E. Shiel and Sarah Jovan conceived and designed the study. Alyssa E. Shiel led the acquisition, analysis, and interpretation of data, and wrote the manuscript. Sarah Jovan contributed to the interpretation of data and edited multiple manuscript drafts. Christina J. Murphy contributed to the acquisition of data and editing of a late-stage draft of the manuscript.

Competing interests
The authors declare no competing interests.

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