Citizen science campaign reveals widespread fallout of contaminated dust from mining activities in the central Peruvian Andes

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Citizen science campaign reveals widespread fallout of contaminated dust from mining activities in the central Peruvian Andes

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ABSTRACT

Inadequate management of mine tailings at Cerro de Pasco, one of Peru's largest mining complexes, has resulted in elevated concentrations of Pb, As, Cu, Zn, and Ag in surface soil horizons across the Junín Plain, central Peru. During June 2016, in response to local concern over mine contamination, teams of local citizens armed with sample bags, plastic trowels, and GPS receivers acquired 385 surface soil samples and 9 plant samples from agricultural lands from an area ~1000 km² on the Junín Plain. Metal concentrations were determined by acid digestion and inductively coupled plasma–mass spectrometry, and results revealed elevated levels of Pb, As, Cu, Zn, and Ag in all samples within a 10 km radius of the center of mining activities, and measurable contamination at least 30 km to the south-southwest, in the direction of prevailing winds. Dust traps emplaced for a 12 month period confirmed that contamination is ongoing. High metal concentrations in grasses growing on contaminated soils revealed that a portion of the total metal contamination is removed from the soil and held in grass tissue, where it can be ingested by graminivores, especially llama, alpaca, and sheep, thereby entering the human food supply.

INTRODUCTION

The ecological and human health effects of exposure to heavy metals can be significant, even at low concentrations (Wuana and Okieimen, 2011; Hayes et al., 2012), and adequate wastewater and dust management are essential to reduce the impact of mining operations beyond the boundaries of mining facilities (Dold, 2008). Studies on the soil-plant-animal elemental pathway have shown that livestock can accumulate heavy metals by grazing in contaminated areas (Abrahams and Thornton, 1994), and consumption of contaminated meat, crops, and drinking water is a major pathway of human metal ingestion (Zhuang and Zou, 2009). Tailings, in particular, can be significant sources of metal contamination (Dold et al., 2009; Csavina et al., 2012), and seasonal moistening of tailings in semiarid regions can produce geochemical weathering products that are particularly susceptible to entrainment by wind (Smuda et al., 2007; Dold et al., 2009; Hayes et al., 2014).

Deflation by eolian processes contributes a range of particle sizes to the atmospheric dust load (Csavina et al., 2012). Soil properties controlling dust production include surface roughness, plant cover, clay and organic matter content, particle-size distribution, and presence or absence of a biocrust (Reheis and Kihl, 1995; Belnap et al., 2001; Csavina et al., 2012). Climatic factors such as wind speed and direction, humidity, depth to groundwater, and the annual distribution of precipitation also affect rates of landscape deflation (Dold et al., 2009; Csavina et al., 2014; Hayes et al., 2014; Kaste et al., 2016). The highest levels of soil contamination by tailings-derived dust are generally found within 1–2 km of source areas, and concentrations decrease sharply with increasing distance (Benin et al., 1999; Csavina et al., 2012; van Geen et al., 2012; Kim et al., 2014). However, measureable contamination may be found up to 50 km from sources (Cartwright et al., 1976; Benin et al., 1999), especially downwind (Csavina et al., 2012; Castillo et al., 2013).

The Cerro de Pasco mining district in central Peru (Fig. 1) includes a large open pit within city limits (Boryga, 2015; Dajer, 2015), the Excelsior waste rock heap, the Quiulacocha inactive tailings facility, and the Ocryoc active tailings facility (Fig. 1). Cerro de Pasco has a legacy of mining since pre-Incan times (Cooke et al., 2008, 2009; Cooke and Abbott, 2008; Dold et al., 2009; Rodbell et al., 2014). Silver was mined at Cerro de Pasco prior to the construction of a railway in the late 1800s CE to facilitate copper mining; the subsequent construction of a smelter (1906 CE) produced lead (Rodbell et al., 2014). The region is located at an elevation of 4000–4500 m and experiences ~1025 mm/yr of precipitation and 988 mm/yr of evaporation, with very little rainfall and low humidity during the austral winter months (June–August; Smuda et al., 2007). As a result, the region's uncovered tailings undergo geochemical transformations, mobilization via surface runoff during the wet season, and subsequent wind erosion during the dry months (Smuda et al., 2007; Dold et al., 2009). Elevated levels of Pb in children in Cerro de Pasco are likely a result of ingesting or inhaling tailings dust and/or contaminated food supplies (Bianchini et al., 2015; Boryga, 2015; Dajer, 2015). Metal concentrations in sediment cores from local lakes that are not hydrologically connected to sources of mine waste record atmospheric deposition far beyond the confines of the mining facility (Cooke and Abbott, 2008; Cooke et al., 2009), whereas direct runoff of contaminated sediment has been shown to enter Lake Junín via the Río San Juan (Fig. 1; Rodbell et al., 2014).

MATERIALS AND METHODS

Field Methods

Surface soil samples ($n = 385$) were collected as part of a citizen science campaign in June 2016 from around Cerro de Pasco and the surrounding Junín Plain. In addition, 12 samples

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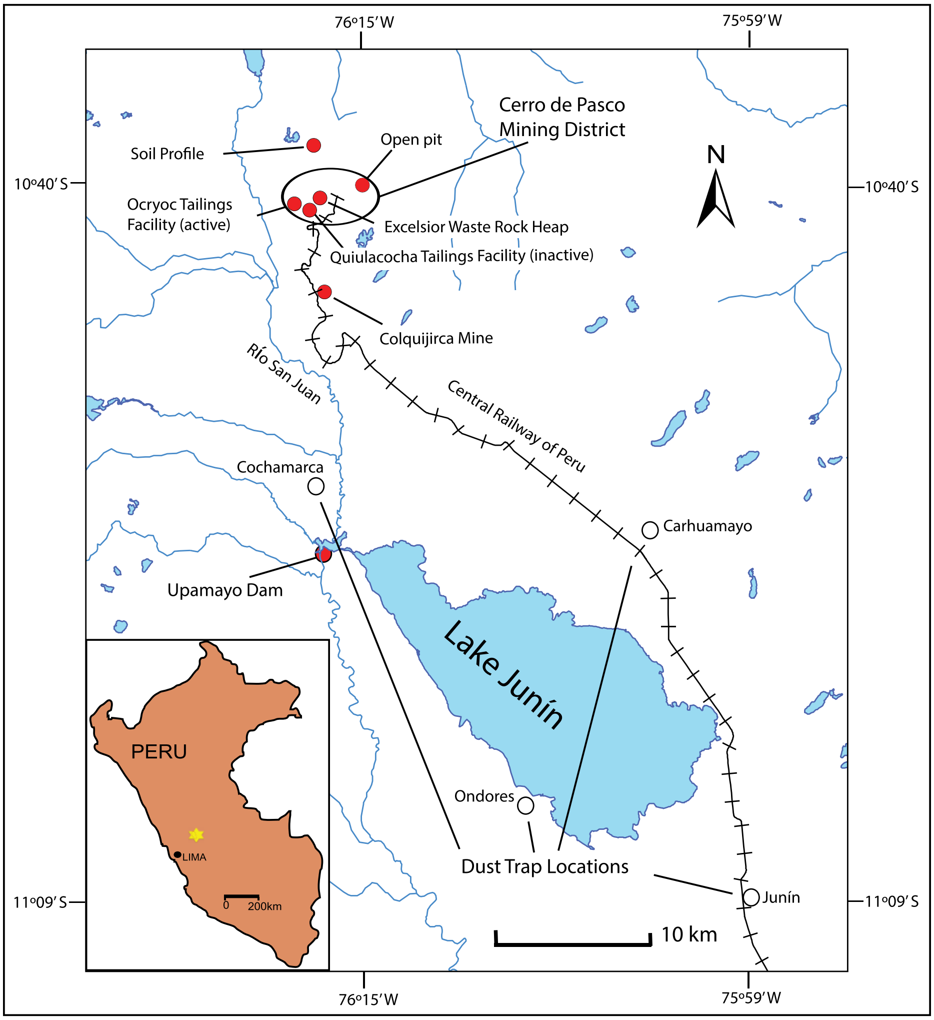

Figure 1. Locations of key mining facilities, dust traps, and soil profile at Cerro de Pasco, cental Peru (Fig. 2). Ocryoc tailings facility, Quiulacocha inactive tailings facility, and Excelsior waste rock heap are likely sources of heavy metal–laden dust to the region. Hachured line indicates railroad tracks.

were collected every 1–5 cm from the upper 35 cm of a soil profile exposed in a road cut through a moraine 4.2 km northwest of the main Cerro de Pasco mining operation (Fig. 1), and 9 samples of juvenile *Stipa ichu* grass (4–8 cm tall) and associated roots were collected from grazing areas at varying distances from Cerro de Pasco.

Bulk dust samples were collected with dust traps made from 43-cm-diameter polycarbonate plastic funnels with an ~6 cm layer of marbles suspended by a nylon mesh screen, based on a modification of the design described by Reheis and Kihl (1995). In total, four dust traps (Fig. S1 in the Supplemental Material[1]) were deployed 2–7 m above ground for one full year (June 2016–June 2017) at municipal centers in Junín, Ondores, Carhuamayo, and Cochamarca (Fig. 1).

Analytical Procedures

Samples were analyzed for Al, Zn, Cu, As, Ag, and Pb using a Perkin Elmer 6100 dynamic reaction cell (DRC) inductively coupled plasma–mass spectrometer (ICP-MS; Tables S1 and S2). Soil samples were oven-dried (50 °C), disaggregated with agate mortar and pestle, and homogenized before digestion of 0.5 g of soil in a mixture of 9.5 mL of 18 MΩ deionized water and 1.0 mL of 70% distilled HNO_3. This procedure, (detailed in the Data Repository), mobilizes weakly bound elements adsorbed to organic and inorganic surfaces, minimizing those held in residual minerals (Cooke et al., 2007; Rodbell et al., 2014). Sediment accumulated in dust traps was centrifuged and decanted until concentrated for freeze drying. Dust samples were then homogenized and digested for trace metal analysis following the aforementioned procedure. Plant samples were washed with deionized water to remove soil and dried overnight at 60 °C, and roots and shoots were separated from one another before acid digestion (see the Data Repository; Table S3).

Data Processing

Data sets of Zn, Cu, As, Ag, and Pb were each subdivided into decile groupings of individual metal concentration. Symbols of different size and color were assigned to the sampling locations within each contamination bracket and plotted on a satellite image.

Because of a lack of Peruvian heavy-metal regulatory limits (Himley, 2012), in order to assess the severity of contamination, the U.S. Environmental Protection Agency (USEPA, 2009) maximum contaminant levels (MCLs) for industrial waste and municipal sludge (USDA, 2000) were compared to soil metal concentrations. Enrichment factors (EFs; Table S4) for soils (Hernandez et al., 2003; Kim et al., 2014) were calculated to quantify the magnitude of contamination of the 90th percentile (P90) of the entire data set of soil metals relative to background metal concentrations. These background values were based on a sample from 18 cm depth, ~4 km north-northwest of Cerro de Pasco (Fig. 2; Table S2). Metal concentrations of soil collected from depth provide appropriate background values because contamination via atmospheric deposition is generally limited to the upper 0–5 cm of soil (Rodríguez et al., 2009; Csavina et al., 2012; Kim et al., 2014). EFs (Table S4) were then calculated as follows:

$$\mathrm{EF} = [\text{P90 metal concentration}] / [\text{background metal concentration}]. \quad (1)$$

Phytoextraction was evaluated by calculating the accumulation factor (AF), which is the ratio of metal concentration in *S. ichu* grass plant tissue to that in adjacent soil (Bech et al., 2012; Ali et al., 2013). Root and shoot metal concentrations were averaged in order to estimate the metal concentration in plant tissue for AF calculations (Table S3). The translocation factor (TF) was calculated as the ratio of metal concentration in plant shoots to that in roots (Table S3).

RESULTS AND DISCUSSION

Extent of Contamination

Concentrations of Zn, Cu, As, Ag, and Pb in surface soil horizons revealed significant spatial variation, which is expected given the history of mining in the region (Cooke et al., 2009). Samples had the highest concentrations of As and Pb relative to U.S. EPA (2009) MCLs for industrial waste (Table S4), and of those we measured, these two elements are of greatest concern to human and ecological health (Wuana and Okieimen, 2011). Enrichment factors were

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[1] Supplemental Material. Metal concentrations in surfaces soils (Table S1), soil profile at Site 2 (Figures S2 and S3; Table S2), plant roots and shoots and adjacent soil (Table S3), and contamination levels, backgrounds, and enrichment factors (Table S4). Please visit https://doi.org/10.1130/GEOL.26213S.12093966 to access the supplemental material, and contact editing@geosociety.org with any questions.

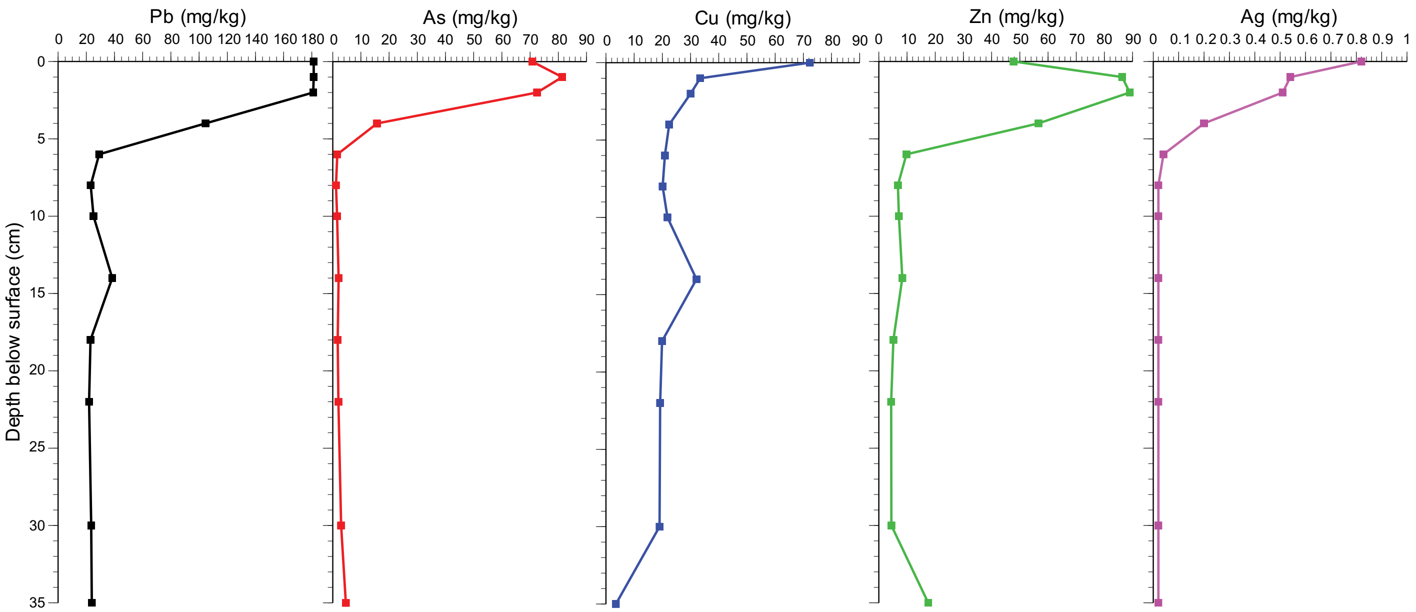

Figure 2. Down-profile variations in metal concentrations from a soil profile ~4.2 km north-northwest of Cerro de Pasco mining complex, central Peru (Fig. 1). Elevated concentrations of Pb, As, Cu, Zn, and Ag are concentrated near the surface and have not leached downward (Table S2 [see footnote 1]).

9.5 (Cu), 70.2 (Zn), 78.1 (As), 107 (Ag), and 133.8 (Pb; Table S4).

The soil depth profile showed the highest concentrations of metals in the top 3 cm (Fig. 2), which is attributed to atmospheric deposition (Rodríguez et al., 2009). Organics and clays retain heavy trace metals at the surface, unlike major elements such as Na, Ca, K, Mg, Fe, and Mn, which can be leached downward during the austral summer wet season (Sauvé et al., 2000; Moreno et al., 2009; Rodríguez et al., 2009; Wuana and Okieimen 2011; Kim et al., 2014).

Spatial Analysis of Contamination

A clear zone of contamination extends many kilometers from the center of mining operations at Cerro de Pasco, where Zn, Cu, As, Ag, and Pb concentrations are well above background levels (Fig. 3). Soil metal concentrations are highest in an area within a 10 km radius of Cerro de Pasco, and these extend at least as far as 30 km on an azimuth heading of 175° to 190° (south-southwest) from Cerro de Pasco. Contamination is most intense ~20 km south-southwest of Cerro de Pasco; beyond this point, concentrations decrease to the edge of sampling coverage, 30 km from the mining district. Sampling to the north and northwest of Cerro de Pasco was restricted by mountainous terrain and limited road access, but it is not expected to be as high as in the region that lies in the direction of the prevailing winds. The south-southwest range of the zone of contamination corresponds with local wind directions (Csavina et al., 2012; Castillo et al., 2013; Kim et al., 2014). During the dry winter months, when entrainment of dust particles is expected to be greatest (Ravi et al., 2004; Smuda et al., 2007; Csavina et al., 2012), southwest and south-southwest wind speeds commonly exceed 28 km/h. The observed extent of contamination and modern wind velocities suggest that entrained particles have an atmospheric residence time of ~1 h and contain high enough concentrations of heavy metals to contaminate terrain tens of kilometers from the origin (Csavina et al., 2012).

Based on the distribution of elevated metal concentrations (Fig. 3), and given the aforementioned wind velocities and prevailing wind direction, the mining operations in and around Cerro de Pasco are the primary sources of contamination. Cerro de Pasco's Quiulacocha and Excelsior inactive mine waste facilities, located 2.5 km from the Cerro de Pasco open pit, are likely the largest sources contributing to the contamination observed over the region. This is due to ongoing geochemical transformations that increase material susceptibility to wind erosion (Smuda et al., 2007; Dold et al., 2009). Other metal sources, such as the Ocryoc tailings pond, Cerro de Pasco open pit, Colquijirca mine, and the seasonally exposed riverbed of the contaminated Río San Juan, could also contribute to atmospheric metal loading (Dold et al., 2009). An additional location of elevated concentration of metals is present near the city of Junín and along the railroad tracks used to transport ore from Cerro de Pasco to the smelters in La Oroya, ~100 km to the south. Localized spillage and/or wind deflation of ore during transport may account for the presence of this contaminated zone ~50 km to the south of the mining district.

Metal Accumulation in Dust Traps

Dust traps revealed spatially variable sedimentation rates and metal concentrations (Table 1). The Cochamarca dust trap had the highest metal concentrations, consistent with its location within the zone of maximum surface soil contamination, ~22 km south-southwest of the mining district (Fig. 1). Although metal concentrations declined with increasing distance from mining operations (Table 1), dust sedimentation rates are variable and do not follow the aforementioned concentration trend. This likely reflects proximity to local dust sources, such as road dust (Castillo et al., 2013; Fernández-Caliani et al., 2013; Sánchez de la Campa et al., 2015), which can re-entrain contaminated material from surrounding surface soils, thus resulting in elevated contaminant flux rates even at sites distal to the source of pollution.

Lead Accumulation in Plants

Stipa ichu grass and root material from contaminated zones revealed 82–600 mg/kg Pb, whereas aboveground material (shoots) contained 15–150 mg/kg Pb (Table S3). The range in TFs for Pb was 10%–66%, and the range in AFs for Pb was from 1%–40% in areas with contaminated soils (Table S3). The quantity of metals removed from soils by *S. ichu* grass is variable (Bech et al., 2012) and relatively low compared to plants specifically used for phytoremediation (Bech et al., 2012; Ali et al., 2013). However, Pb accumulation in plants was observed, and where grass cover was dense, the grasses contained a fraction of the total metals that have been deposited, and this is not reflected in the soil metal concentration maps (Fig. 3).

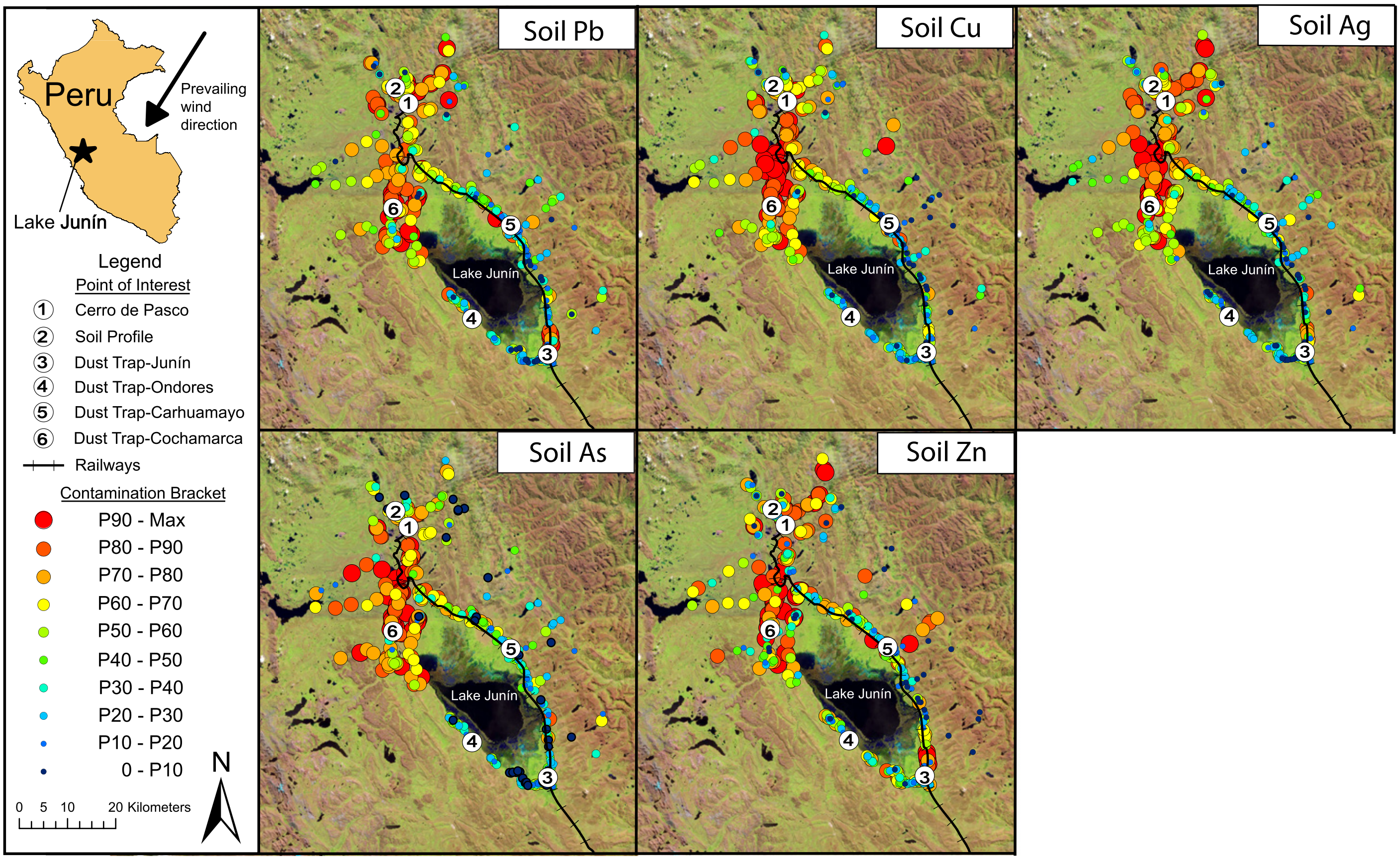

Figure 3. Spatial distribution of Pb, Cu, Ag, As, and Zn concentration in soils on the Junín Plain, central Peru (Table S1 [see footnote 1]). Contamination brackets show the magnitude of contamination of the Xth percentile of the data. Elevated concentrations are evident within 10 km of Cerro de Pasco (~10°40'S; 76°15'W; 4350 masl), and also extending ~30 km south-southwest, corresponding with prevailing wind speeds and direction. Satellite image is from earthexplorer.usgs.gov, *Sentinel-1*.

TABLE 1. RESULTS OF DUST TRAPS INSTALLED AROUND LAKE JUNÍN IN CENTRAL PERU IN JUNE 2016

Dust trap location	Approximate distance from tailings (km)	Metal concentration (mg/kg)					Total dust accumulation (g)	Dust sedimentation rate ($g/m^2/yr$)*
		Pb	As	Cu	Zn	Ag		
Junín	52	159	9.9	19.6	295	0.026	4.24	28.8
Ondores	42	249	17.3	40.4	362	0.046	1.03	7.0
Carhuamayo	26	252	14.0	55.5	518	0.113	0.74	5.0
Cochamarca	22	531	29.9	109.0	446	0.410	0.34	2.3

*Sedimentation rate is based on 43.2-cm-diameter dust trap and 1 yr of accumulation.

Agricultural land use on the Junín Plain is primarily for graminivores (lamas, alpacas, and sheep), and *S. ichu* grass is a major component of livestock diet. Metal contamination of plants on agricultural and pasture land is thus a potential pathway for metal ingestion by humans in the area (Abrahams and Thornton, 1994; Zhuang and Zou, 2009), and export of agricultural products could potentially affect humans in areas beyond the Cerro de Pasco–Junín region.

CONCLUSIONS

Elemental data reveal a distinct pattern of elevated heavy metal concentrations in soil within ~10 km of the Cerro de Pasco mining district in all directions; elevated concentrations also extend at least 30 km southwest to south-southwest, in the direction of prevailing winds. Mean monthly dry season wind speeds of 28 km/h suggest a mean residence time of contaminated dust in the atmosphere of ~1 h, which is of sufficient duration for dust to be inhaled by residents. Soils retain metals in the upper 3–5 cm, with limited downward leaching, and measurable masses of Pb and other metals are pulled from soil and accumulate in harvestable plant material that is commonly consumed by graminivores in the region. The concentration of metals in modern dust traps decreased with increasing distance from the Cerro de Pasco mining district, but dust sedimentation rates and thus the flux of heavy metals are highly variable and are affected by the re-entrainment of dust at local source areas, such as gravel roads. The data presented here provide evidence that the management of mine tailings at the Cerro de Pasco complex has been inadequate, and it has resulted in the contamination of nearby areas with heavy metals, putting humans, livestock, water sources, and agricultural lands at risk. A similar pattern of contamination can be expected from exposed mine waste deposits in other regions, wherever there is a strong seasonality of precipitation, strong winds, and uncovered tailings.

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