

Collaboration with Nlaka'pamux communities to examine metal deposition on soapberry in interior British Columbia

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Abstract. This paper presents a collaboration with Indigenous Nlaka'pamux communities to develop a study to address the effects of mining dust on soapberry (*Shepherdia canadensis*), which is an important medicinal and food resource for local Nlaka'pamux people. The objectives were to compare element concentrations in samples of washed and unwashed leaves and berries relative to soil samples collected around the mine and in a reference area. Samples were analyzed for metal concentrations using inductively coupled plasma mass spectrometry (ICP-MS). Spatial models showed that six metals (Al, Ba, Cu, Fe, Pb, and Sr) had significant elevated concentrations near the mine compared to farther away, though concentrations were generally within ranges reported for human consumption. There was no correspondence with soil metal concentrations, suggesting that elevated metal concentrations in leaves and berries near the mine were due to dust rather than uptake from local soils. Washing of leaves and berries reduced concentrations by between 13 and 48%, depending on the metal. The study illustrates a model with global relevance for how mines can work with communities to address complex social–ecological problems.

Key words: biomonitoring; fugitive dust; geostatistical spatial models; Indigenous people; soapberry; surface mining.

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INTRODUCTION

In this study, we examine the effects of fugitive dust from the Highland Valley Copper (HVC) mine in central-interior British Columbia on soapberry (*Shepherdia canadensis* [L.] Nutt.), an important food and medicinal plant of the Indigenous Nlaka'pamux people. In recent years, local Nlaka'pamux people expressed concerns about the escape of dust from the HVC mine and its potential impact on surrounding ecosystems, including on plants and animals. In response, HVC engaged Nlaka'pamux communities to

collaboratively develop a study to address their concerns. The study consisted of two parts: (1) a lichen biomonitoring study (in preparation) to describe the extent and magnitude of dust deposition from the mine and (2) a soapberry biomonitoring study (i.e., the work presented here) to examine the potential effects of dust deposition on a plant of concern and cultural importance to Nlaka'pamux people.

Mine sites can be significant sources of fugitive dust containing metal contaminants, with potential negative effects on surrounding ecosystems. Windblown particulate matter can be released

from mine tailings impoundments, traffic, and activities such as blasting and milling and then transported and deposited on vegetation and soil in downwind areas. Plants and animals generally require trace amounts of certain elements to maintain normal nutrition and growth, but large amounts of the same elements can lead to chronic or acute toxicity (Adriano 2001). For plants in particular, the potential risks associated with deposition of metal contaminants from mining can include reduced plant growth (Athar and Ahmad 2002) and reproduction (Ryser and Sauder 2006), which can lead to impacts on the population, community, and ecosystem level. Plants have also been shown to take up and accumulate metals (Amin and Ahmad 2015), which can then bioaccumulate in the food chain and lead to impacts in animals and humans (Gall et al. 2015).

Methods to examine metals in fugitive dust from mining often involve dust-sampling equipment or biological receptors. There is a range of dust-sampling equipment (see Csavina et al. 2012), but installation and operation can be cost prohibitive to achieve adequate sampling density around large mine sites. As a cost-effective alternative, many researchers have studied metal deposition using biological receptors, including lichens (Balabanova et al. 2012), mosses (Neitlich et al. 2017), and vascular plants (Stachiw et al. 2019). Lichens and mosses tend to be the organism most frequently used due to their capacity for metal accumulation, while far fewer studies rely on vascular plants.

Based on input from Nlaka'pamux communities, for this study, we used soapberry (pronounced *sxwúsm* in the local Nlaka'pamux language) as our biological receptor. Soapberry is a deciduous, spreading shrub that reaches 1–2 m in height and is widespread at low to sub-alpine elevations in dry to moist open forests and clearings (Parish et al. 1996). The plant is ubiquitous across the region and is an excellent bioindicator because it has substantial leaf surface area and has unique morphological characteristics (e.g., hairy leaves and sticky berries) that result in accumulation of dust particles on the plant. Nlaka'pamux people harvest the leaves and berries of the soapberry plant for a number of purposes: Leaves are used as an ingredient for several types of tea in combination with other

plants, and berries are jarred whole or as a concentrate and used to make a whipped confection or diluted as a beverage (Turner and Burton 2010).

The Nlaka'pamux people have occupied the lands of the Highland Valley area for thousands of years up until the onset of mining. Today, Nlaka'pamux people continue to visit the area for hunting, fishing, gathering, and other traditional activities, though the landscape has changed dramatically in recent decades due to mining and logging. The HVC mine covers approximately 6800 hectares and the mine releases a significant amount of dust, including from the tailings facility, waste-rock deposition, and haul roads. Logging and its attendant network of roads have also been extensive in the area, causing added dust and increased public access. HVC has various dust-management mitigations in place, including dust domes covering the main ore piles, covered haulage of concentrate products, and an ongoing dust monitoring program that includes dust-fall and air-quality monitoring stations.

We pursued the following research questions: (1) Is mining dust being deposited on soapberry plants? (2) Where on the landscape is soapberry most affected by mining dust? (3) Which of the deposited elements are most concerning from a plant, animal, and human health perspective, relative to the literature? (4) Does washing the plant material reduce element content? We developed and examined these questions through extensive collaboration with Nlaka'pamux communities to ensure that the work meaningfully addressed their concerns.

MATERIALS AND METHODS

Study area

The study area is in the Highland Valley in south-central British Columbia, approximately 70 km southwest of Kamloops (50°28'22 N, 121°01'16 W) (Fig. 1). The study area varies in elevation from around 360 to 1720 m. The HVC mine is a large open-pit mine located in the Highland Valley. Mining at the site commenced in 1962, and the mine is now one of the largest open-pit copper mines in the world, producing approximately 1% of the world's copper concentrate and 1.5% of the world's molybdenum. The HVC mine is majority owned by Teck Resources.

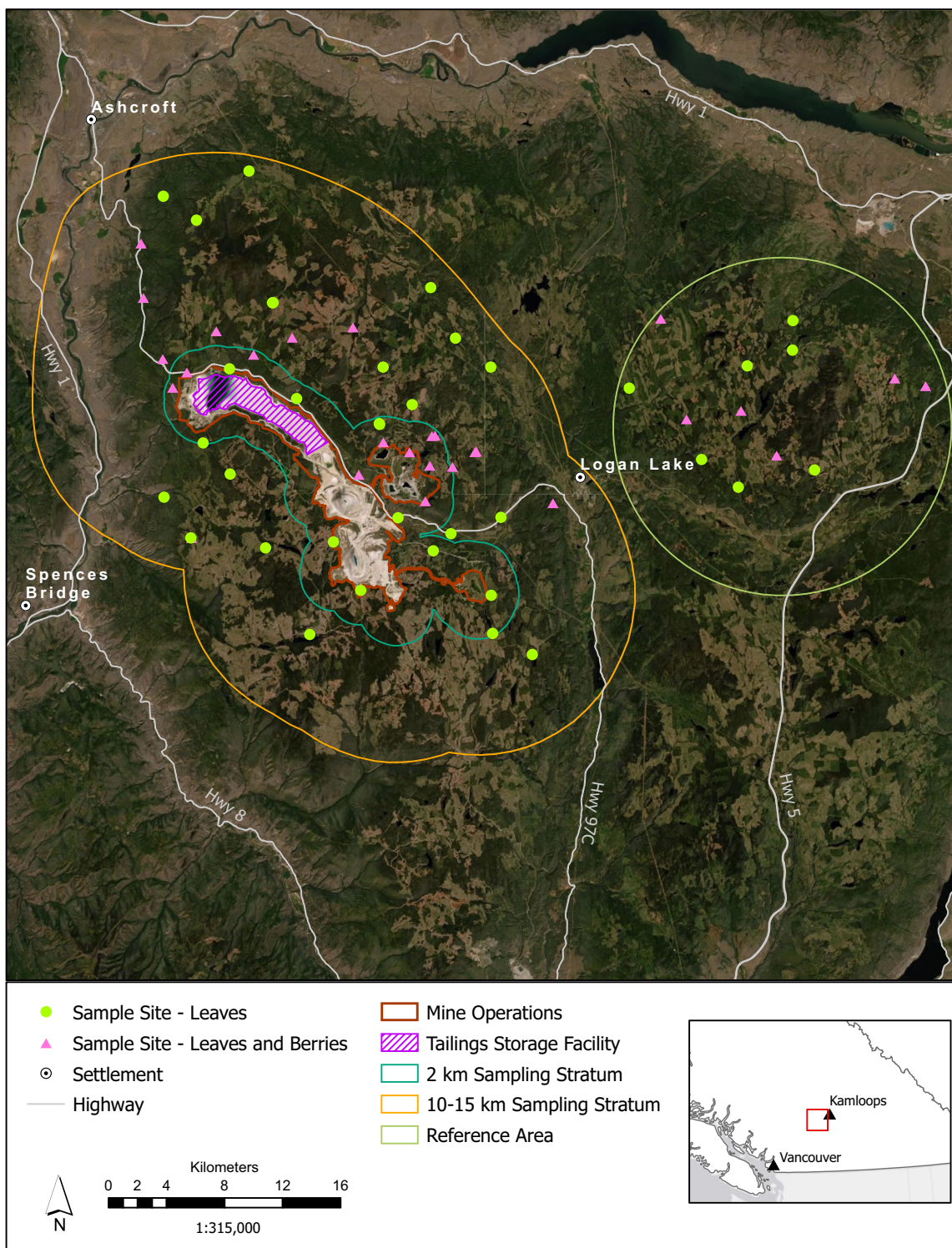


Fig. 1. Sample site locations for soapberry leaves and berries within sampling strata in the mine study area and the reference study area. Key dust source areas include the mine area, the tailings storage facility, and Highway 97C heading north, which is the main haul road corridor for transporting copper concentrate.

The Highland Valley study area is located within the Thompson Plateau physiographic subdivision (Holland 1976). Parent materials consist largely of moderately fine-textured glacial till and major soil groups are predominantly Eutric and Dystric Brunisols, as well as localized occurrence of Melanic Brunisols, Gray Luvisols, and Humo-Ferric Podzols (Valentine et al. 1994). Major vegetation types include interior Douglas-fir forests in valley bottoms and montane spruce forests on valley sides. Engelmann spruce forests occur at the highest elevations. The climate is humid continental microthermal (Dfb) with cold dry winters and hot dry summers (Kottek et al. 2006). Mean monthly temperatures range from around -6°C in January to 15°C in July through August and mean monthly precipitation ranges from around 17 mm in March to 48 mm in June. We carried out fieldwork in the late summer months of 2014, which was generally hot and dry with a mean monthly temperature of 24°C and a mean monthly precipitation of 31 mm. The prevailing winds in the study area are from the southwest.

We carried out fieldwork in the summer of 2014 in two study areas: (1) a “mine study area” and (2) a “reference study area.” The mine study area was an area around the mine boundary, extending 15 km from the mine boundary to the north and 10 km in all other areas (approximately 126,840 ha, including the mine area; Fig. 1). The mine study area extended further to the north because results from a pilot study demonstrated that prevailing winds carried dust further in this direction. The reference study area was an area approximately 12 km to the east of the mine boundary and was intended to represent a non-industrialized area, with little influence from mining activities; the area was not intended to represent “background” concentrations of elements in remote locations. The area was selected based on guidance from Nlaka’pamux members during community workshops, where members indicated that they observed this area to be relatively free of dust and safe for berry picking. The reference study area is topographically separated from the mine study area by a valley ridge and is characterized by a similar range of vegetation types and elevations as the mine study area.

Community meetings

We conducted six community meetings involving semi-structured and open-ended interview techniques between 2013 and 2015. The first two meetings involved discussions about concerns related to dust in the Highland Valley area, and members reached consensus to focus the study on soapberry. The third meeting involved more focused discussion about study design and methodology. We integrated community input and developed a study design and methods for verification by members at a fourth meeting, which involved a field visit where members shared knowledge and harvesting techniques. The aim of the fifth meeting was to present preliminary results, and the sixth meeting involved verification of final results and deliverables.

Sample design and collection

We sampled 63 sites, including 50 sites in the mine study area and 13 sites in the reference area. The 50 sites included five autocorrelation sites, which are sites that are spatially paired with a main sample site (i.e., located ~ 50 m away) and serve to quantify local spatial variation among sites. We preselected sites based on two criteria to represent the habitat types that Nlaka’pamux people target for berry picking, as described to us in the community workshops: (1) accessible from roads and (2) located within mature forest cover, at least 50 m from roads or cutblocks. Selecting sites within mature forest areas helped to maintain consistency in the types of forest habitats that we were sampling and to limit the effects of other potential isolated dust sources, such as roads and forest cutblocks in the area. For the mine study area, preselected sites were arranged using a distance- and direction-stratified sample design, with more intensive sampling in areas of high dust deposition. Stratification was necessary to improve precision and reduce site-to-site variability, which is generally greater in areas where dust deposition is highest. The 50 sites were stratified within two distance strata: 22 sites within 0–2 km of the mine boundary, and 28 sites within 2–10 km of the mine boundary (2–15 km in the north) (Fig. 1). The 13 sites in the reference area were evenly distributed using a grid-based sample design.

At all 63 sites, we measured site characteristics and sampled soapberry leaves and soil. At each

site, we established a 15-m fixed radius plot to measure: (1) percent canopy cover using a densiometer; (2) percent composition of tree species in canopy and sub-canopy; (3) stand age by extracting a core at breast height (1.3 m) of one representative live tree per plot; (4) topography, including elevation, slope, and aspect; and (5) vegetation type based on Biogeoclimatic Ecosystem Classification (BEC) standards for the Kamloops Forest Region (Lloyd et al. 1990). We collected around 50 g of first-year soapberry leaves and new shoots (i.e., the parts of the plant that Nlaka'pamux people use for tea and medicine, hereafter referred to as "leaves" and "leaf") from upper and lower portions of six plants per site (Fig. 2). Powderless nitrile gloves were used when handling the plants, and leaf samples were placed into polyethylene sample bags in coolers and then frozen until processing at the laboratory, which occurred immediately after the field

season. We collected duplicate leaf samples at eight sites (17% of sites) to assess intra-site variability.

Soil samples were obtained by digging a soil pit to 40 cm and extracting composite samples of surface (0–20 cm) and subsurface (20–40 cm) mineral soil from the sides of the pit for the entire depth ranges. Soil profiles generally consisted of Bm horizons, as the dominant soils in the study area are Brunisols. Standard textures were generally sandy loams, which are relatively consistent throughout the study area. The samples were collected in polyethylene WhirlPak sample bags and frozen until processing at the laboratory. The purpose of soil sampling was to characterize naturally occurring metal concentrations in the local mineral soil and determine if concentrations in soapberry were linked to local and non-anthropogenically derived dust or metal uptake through roots from local soils, as opposed to dust



Fig. 2. Leaves and berries of soapberry (*Shepherdia canadensis*) (A); collecting first-year leaves and new shoots (B); collected sample of whole berries (C); and preparing juice samples from berries (D).

accumulation on foliage and foliar uptake following mining dust deposition on plant surfaces.

Samples of whole berries, berries for juice, and leaves for tea occurred at subsets of the 63 sites. Leaf samples for tea were collected from 24 sites. Samples of berries were collected from 27 sites (Fig. 1), nine of which provided enough berries to make juice. Fewer sites were sampled for juice because berry abundance was limited due to hot and dry conditions, requiring us to prioritize whole berries over berries for juice. Berry sampling involved knocking berries into a sterilized bucket by hitting the branches with a stick, which is a common harvest technique used by Nlaka'pamux people. Berries were sampled from at least 6 plants per plot, and we collected a minimum of two cups (~500 mL), which provided enough material for an unwashed/washed pair of whole berry samples.

Sample preparation

Berry samples were processed in the field by removing coarse debris and then preparing unwashed/washed pairs by rinsing half of each sample (~1 cup) one time with around 2 L of demineralized water in a stainless-steel colander for around 30 s. Whole berry samples were transferred into polyethylene bags that were frozen until analysis at the laboratory. Juice samples were prepared in a kitchen using a sterilized stainless-steel food mill to crush the berries and capture the juice. The juice samples were canned in 50 mL canning jars using a boiling water bath. Jars were stored at room temperature until laboratory analysis.

In the laboratory, unwashed/washed leaf sample pairs were prepared by rinsing half of each sample (~25 g) one time with around 2 L of demineralized water in a stainless-steel colander for around 30 s, then drying all samples at 70°C overnight, and grinding in a coffee mill to homogenize. Leaves for unwashed tea samples were rinsed and then dried but not homogenized (washed tea samples were not prepared). Tea samples were prepared by adding 4 g dried leaves to 250 mL of boiled distilled water and then steeping for 5 min before filtering to remove leaves. Soil samples were air-dried until they created a dust when crushed to check for dryness and then oven-dried at 35°C. Samples were then sieved through a 2-mm sieve.

When preparing the juice and tea samples, we endeavored to follow the guidance and replicate the preparation methods shared by Nlaka'pamux members during the community workshops. However, we acknowledge the potential contamination risks associated with this approach, including possible contribution of trace metals by glass canning jars, the coffee mill, and filter paper, etc.

Laboratory analysis

All soapberry and soil samples were analyzed for element concentrations using ICP-MS. We considered leaves and berries as the main environmental receptors receiving fugitive mining dust, and therefore, we analyzed both sample types for a full suite of 33 elements (see Appendix S1, Table S1). As derivatives of leaves and berries, tea and juice were only analyzed for the elements that were found to be elevated in leaves and berries. Prior to ICP-MS, all samples were digested with nitric acid and hydrochloric acid for 2 h at $95 \pm 5^\circ\text{C}$. Vegetation samples were further digested with hydrogen peroxide for 1 h at $95 \pm 5^\circ\text{C}$. Quality control (QC) protocols for ICP-MS analyses included the following: (i) testing for contamination by comparing element concentrations of method blanks to reportable detection limits (RDL); (ii) testing for accuracy by ensuring that percent recovery of matrix spikes fell between QC limits of 75–125%, and by comparing element concentrations to certified reference materials (CRM); and (iii) testing for precision (i.e., repeatability) by running duplicates every 1 in 20 samples and ensuring that the relative percent difference (RPD) between duplicate values stayed within QC limits of 25–35%.

Statistical methods

Of the 33 elements analyzed in the laboratory, we selected 13 elements for in-depth statistical analysis. The selection was made using the scatterplot matrix function in SAS JMP IN[®] ver. 11 (SAS Institute Inc., Cary, NC) to screen the 33 elements for relationships between concentration and four covariates, including distance to mine, distance to Highway 97C, distance to tailings facilities, and elevation. We analyzed concentration data of the 13 elements using four statistical methods, including the following: (1) simple

linear regression; (2) spatial regression modeling and mapping; (3) multiple regression; and (4) paired *t*-test (see Appendices S2 through S14 for detailed statistical descriptions for each of the 13 elements).

Simple linear regression.—For all 13 elements, six simple linear regressions (e.g., Montgomery and Peck 1992, p. 7) were used where the predictor variable was the natural log of element concentration in either the surface or subsurface soils, and the response variable was element concentration in either soapberry leaves, tea, or berries. The response variables were averaged by site (i.e., across laboratory replicates, field duplicates, and years), and sites were assumed independent.

Spatial multiple regression.—A spatial linear model (e.g., Ver Hoef et al. 2001) was used to (1) estimate the effects of environmental variables on element concentrations in leaves, (2) test differences in element concentrations between the mine study area and the reference area, and (3) map element concentrations across the study area using predictive models. Spatial coordinates of sites were converted to transverse Mercator using the mean of the sample longitudes as the central meridian (e.g., Snyder 1997); this is a distance-preserving projection with minimal distortion. The response variable in the model was leaf element concentration, and predictor variables included the following: elevation, slope, aspect, stand age, canopy cover, distance from key dust source areas, and a categorical variable to allow the intercept to be different between the mine area and the reference area. We excluded BEC zone as a predictor variable because it was highly correlated with elevation. The response and distance variables were transformed with the natural logarithm (Duinker et al. 1992).

Like Hasselbach et al. (2005) and Neitlich et al. (2017), we adopted a spatial linear model that included spatial autocorrelation among sites, random effects for variation due to duplicate samples within site, and variation due to replicated laboratory analyses. A spherical model (e.g., Cressie 1993, p. 61) was used for spatial autocorrelation. Spatial models were fit using restricted maximum likelihood (REML, Patterson and Thompson 1971, 1974) because it performs better than maximum likelihood (Ver Hoef and Cressie 2001). Note that because we used REML,

it is not possible to use AIC (Akaike 1973) for model selection of predictor variables (Verbeke and Molenberghs 2000, p. 75). Instead, all predictor variables were included in the model, and then, stepwise elimination was used to remove predictor variables with the highest P-values (one at a time, refitting the model each time), until all remaining predictor variables had P-values less than 0.15. Outliers were examined with boxplots of residuals, and residuals were plotted against fitted values to check for non-constant variance. Outliers were removed using cross-validation residuals, where each datum was removed one at a time and then predicted from the remaining data. If the absolute difference between the true and predicted values, divided by the prediction standard error, was greater than 3, the datum was deemed an outlier.

To make maps, we could not use the model described in the previous paragraph because some predictor variables were only measured on-site, such as stand age. Therefore, we created a new set of models using only predictor variables for which we had complete spatial knowledge, which included a binary variable for reference site, elevation, the three distance-to-source variables, slope, and aspect. Universal kriging is a method that combines predictor variables with kriging to make predictions at unsampled locations (Cressie 1993, p. 151). Universal kriging predictions were made at locations on a 250-m grid covering the entire study area and they were back-transformed from the log scale. The back-transformations created predictions of median element concentrations in leaves on the original scale, and we produced interpolation maps for each element. Universal kriging also provides prediction standard errors, and 95% prediction intervals on the log scale were computed by taking the predictions plus and minus 1.96 times the standard error. These prediction intervals were back-transformed as well, as quantiles are preserved with monotonic transformations (Chiles and Delfiner 2009, p. 191). Maps were generated using ArcMap (ESRI 2014) from the prediction values, and subjective colors were added based on natural breaks. Maps of the lower and upper bounds, based on the pointwise standard errors, were also produced. The predicted concentrations do not provide absolute deposition values, but rather provide a regional

spatial picture of median element accumulation in leaves, which is a measure of relative element deposition.

To compare element concentrations between the mine study area and the reference area, for each element, we estimated the average concentration in the reference area using block kriging (Cressie 1993, p. 124) and then subtracted the block averages from the point-wise predictions in the study area. We assumed the reference area was far enough from the study area to be independent, which allowed us to sum the block average variance and the point-wise variances to get variances (and standard errors by taking the square root) of the difference. Maps were generated for each element to indicate all locations where the predicted study area values were significantly different from the average reference block value. Zones of significant differences were highlighted with contours on the map.

Multiple regression.—Classical regression combined with stepwise selection was used to examine covariate effects on element concentrations in tea, berry, and juice samples. Spatial models were not used for these analyses because sample sizes were insufficient to estimate covariance parameters reliably. The response variable in the model was element concentration in tea, berry, and juice samples. The covariates were the same as outlined above for spatial regression modeling and mapping. The dependent and distance variables were transformed with the natural logarithm (Duinker et al. 1992). The stepwise selection procedure that was used with regression was the stepAIC function (Venables and Ripley 2013) in the MASS package of the R statistical software system. This procedure uses both forward and backward elimination of covariates based on AIC values.

Paired t-test.—Paired comparisons t-tests (e.g., Snedecor and Cochran 1980, p. 88) were used on element concentration data that were natural log transformed to compare washed and unwashed pairs for leaves, berries, and juice. The data were analyzed on the log scale, and we are therefore calculating proportional changes in the data.

RESULTS

The concentrations of six metals (aluminum, barium, copper, iron, lead, strontium) in

soapberry leaves and/or berries decreased significantly ($P < 0.01$) with increasing distance from the mine (Table 1). Weaker relationships ($P < 0.05$) of lead concentrations in leaves and berries were also evident. No other elements showed significant patterns related to distance and they are no longer discussed further in the paper.

Leaves

Leaf concentrations for two metals (Cu and Fe) decreased significantly with increasing distance from the mine and from the Highway 97C corridor (the main route used for transporting copper concentrate). No other elements analyzed in leaves showed significant negative relationships with distance from mine, though lead and strontium showed significant positive relationships with distance and elevation, respectively, and aluminum had a significant positive relationship with canopy cover (Table 1). Copper concentrations in leaves were also higher on west-facing

Table 1. Coefficient table of final fitted spatial regression models for elements with concentrations in soapberry leaves and berries that had a significant ($P < 0.01$) relationship with covariates in the model.

Element	Covariate	Estimate	SE	T	P
Leaves ($n = 63$)					
Al	Canopy cover	0.72	0.26	2.7	<0.01
Cu	Hwy 97C	−0.22	0.03	−6.93	<0.01
Cu	Eastness	−0.23	0.07	−3.43	<0.01
Fe	Tailings facility	−0.23	0.07	−3.14	<0.01
Pb	Tailings facility	0.15	0.06	2.57	0.01
Sr	Elevation	0.0004	0.0001	3.98	<0.01
Tea ($n = 24$)					
Sr	Hwy 97C	−0.19	0.07	−2.68	0.01
Sr	Elevation	0.002	0.0006	3.44	<0.01
Berries ($n = 24$)					
Al	Tailings facility	−0.74	0.21	−3.59	<0.01
Al	Elevation	−0.002	0.008	−3.02	<0.01
Ba	Hwy 97C	−0.34	0.11	−2.95	<0.01
Fe	Tailings facility	−0.49	0.15	−3.30	<0.01
Pb	Hwy 97C	−0.19	0.08	−2.35	0.03
Sr	Hwy 97C	−0.38	0.11	−3.37	<0.01
Juice ($n = 9$)					
Ba	Hwy 97C	−1.03	0.21	−5.02	<0.01

Notes: Weaker relationships ($P < 0.05$) of lead concentrations in leaves and berries are also presented. See Appendix S1 (Tables S2 and S3) for coefficients for all 13 elements examined for leaves and berries.

slopes, likely due to prevailing winds from the southwest. Spatially, copper concentrations were highest in the area directly around the mine area, and to the northeast (Fig. 3A). This area and a corridor around Highway 97C were significantly higher than the reference area, as shown by the purple line demarking the threshold. Lower bounds for concentration levels near the mine were around 30% prediction confidence (Fig. 3C), whereas upper bounds to the northwest of the mining area were significantly less, with evidence they were unlikely to be above 5% prediction confidence (Fig. 3B). For iron, concentrations in the mine study area were statistically higher than the reference area only in a very small rim around part of the tailings facility (see Appendix S9). There were no specific areas within the mine study area where concentrations of aluminum, strontium, or lead in leaves were significantly different from concentrations in the reference area.

There were no relationships between metal concentrations in leaves and surface or subsurface soil for either copper (Fig. 4), iron, aluminum, lead, or strontium (Table 2). In addition to the difference from the reference area, this lack of correspondence with soil element concentrations suggests that the higher concentrations of copper and iron in leaves are likely due to fugitive mining dust deposition and uptake by or adherence on the leaves, rather than from local and non-anthropogenically derived dust, or from metal uptake through roots. Elevated concentrations may also represent some contribution of road dust deposition, as research shows that road dust can penetrate forest cover beyond the 50 m buffer we used when locating sample sites (Walker and Everett 1987, Santelmann and Gorham 1988).

We calculated a crustal enrichment factor (EF) for copper (relative to aluminum) following the approach Stachiw et al. (2019); this EF ranged from ~60 to over 3000 at some sites, indicating that copper is 60–3000 times more abundant in leaves relative to aluminum than in the Earth's crust. Of the nine sites with highest EF (>1000), seven were within the area delineated as having significantly higher leaf copper concentrations than reference sites. Sampled tailing materials had EFs for copper similar (~1000) to those observed in near-source leaves.

For tea made from soapberry leaves, there were no relationships between copper or iron concentrations in tea with distance from the mine, though there was a negative relationship between strontium concentrations in tea with distance from the Highway 97C, as well as a positive relationship between strontium concentrations in tea with elevation (Table 1). There were no relationships between concentrations in tea and surface or subsurface soil for copper, iron, strontium, or any other elements (Table 2).

Berries

Berry concentrations for four metals (Al, Ba, Fe, and Sr) decreased with increasing distance from the mine (Table 1). Aluminum and iron concentrations decreased with increasing distance from the tailings facility, while concentrations of barium and strontium decreased with increasing distance from the Highway 97C corridor. Aluminum concentrations in berries also decreased with increasing elevation, which is related to distance. A weak negative relationship between lead concentration in berries and distance to Highway 97C was also evident. There was no correspondence between concentrations in berries with surface or subsurface soil for aluminum, barium, iron, strontium, or lead (Table 2). Of these same four metals in juice, only barium significantly decreased with increasing distance from the mine (Table 1), and there was no relationship between concentrations in juice with surface or subsurface soil (Table 2).

Washing test

Washing reduced the concentrations of most of the metals identified above as elevated in leaves and berries. For leaves, washing significantly reduced the concentrations of four metals (Al, Cu, Fe, and Pb) by between 15 and 27% (Table 3). For berries, washing significantly reduced the concentrations of all six metals (Al, Ba, Cu, Fe, Pb, and Sr), with reductions ranging from 13 to 48%. Aluminum had the greatest percent reductions from washing for both leaves and berries.

DISCUSSION

This study addresses a key concern among Nlaka'pamux community members with respect to the magnitude and extent of mining dust

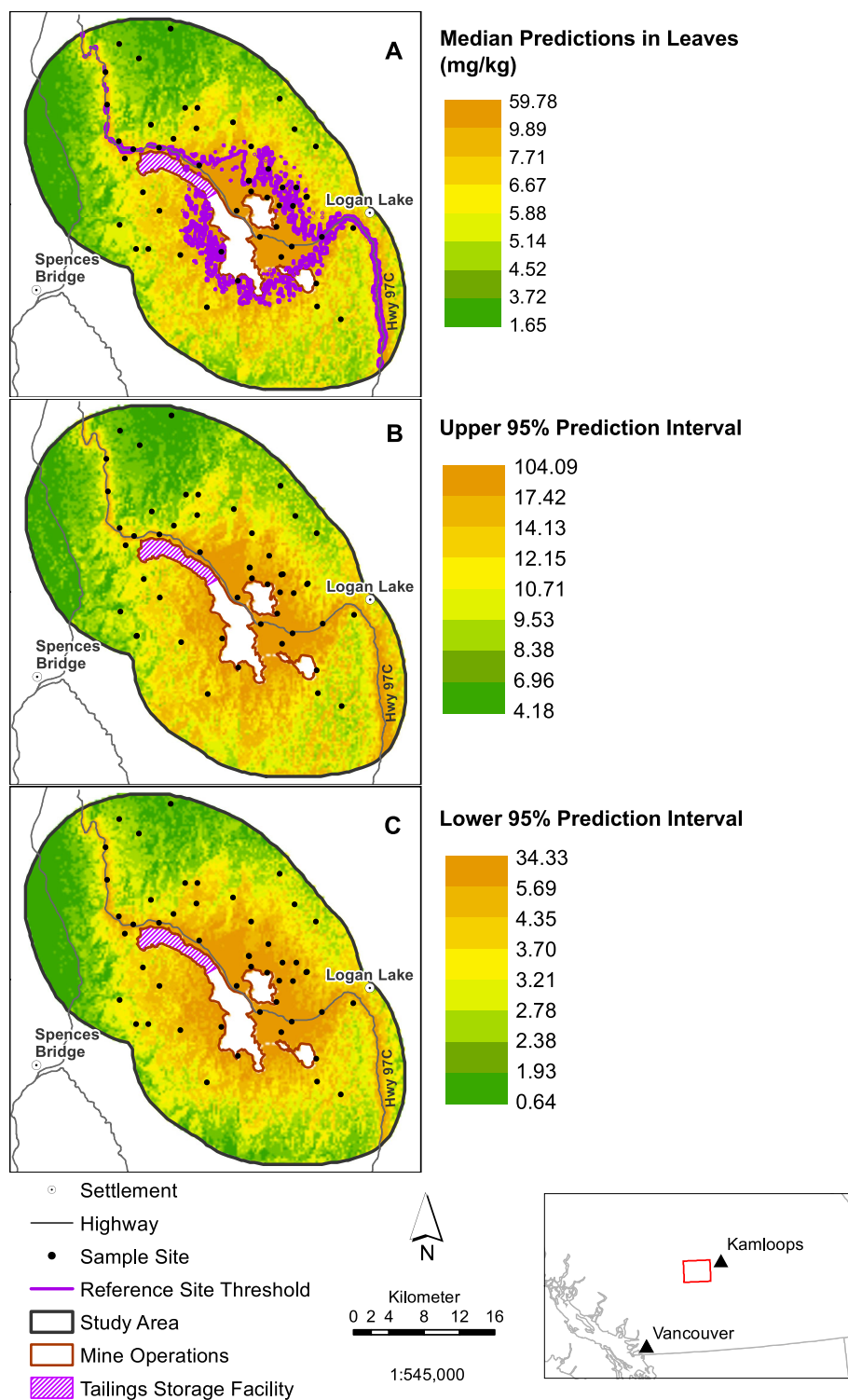


Fig. 3. Median predictions (A) and upper/lower 95% prediction intervals (B, C) of copper concentration in soapberry leaves across the mine study area. All points within the turquoise line on map A have higher levels of copper than in the reference study area.

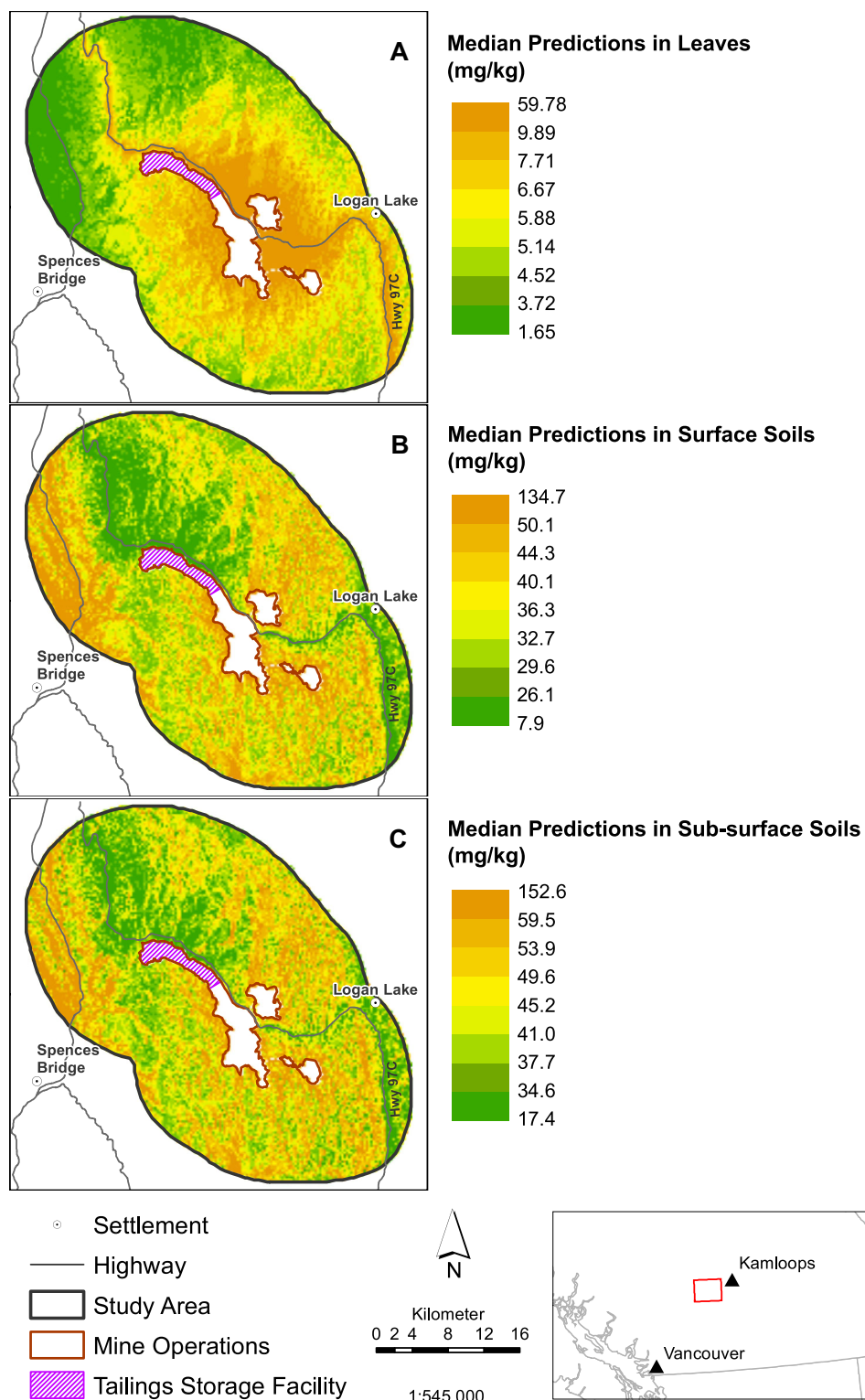


Fig. 4. Median predictions of copper concentration in soapberry leaves compared to surface and subsurface soils across the mine study area.

Table 2. Coefficient table of classical regression models for relationships of element concentrations between soapberry and surface and subsurface soil samples.

Metals	Soil depth	Sample size	Estimate	SE	<i>T</i>	<i>P</i>
Leaves (<i>n</i> = 50)						
Al	Surface	60	−0.27	0.17	−1.63	0.11
Al	Subsurface	58	−0.34	0.20	−1.72	0.09
Cu	Surface	60	0.10	0.11	0.94	0.35
Cu	Subsurface	58	0.03	0.14	0.22	0.83
Fe	Surface	60	−0.16	0.20	−0.78	0.44
Fe	Subsurface	58	−0.19	0.22	−0.85	0.40
Pb	Surface	60	−0.39	0.25	−1.57	0.12
Pb	Subsurface	58	−0.28	0.16	−1.78	0.08
Sr	Surface	60	−0.15	0.17	−0.90	0.37
Sr	Subsurface	58	0.05	0.16	0.32	0.75
Tea (<i>n</i> = 19)						
Al	Surface	23	−0.10	0.33	−0.29	0.77
Al	Subsurface	23	−0.07	0.27	−0.26	0.80
Cu	Surface	22	−0.09	0.10	−0.89	0.38
Cu	Subsurface	22	−0.13	0.09	−1.45	0.16
Fe	Surface	23	0.001	0.44	0.003	1.0
Fe	Subsurface	23	−0.15	0.40	−0.38	0.71
Pb	Surface	23	0.31	0.12	2.65	0.02
Pb	Subsurface	23	0.12	0.08	1.51	0.15
Sr	Surface	23	−0.36	0.29	−1.22	0.24
Sr	Subsurface	23	−0.07	0.35	−0.20	0.85
Berries (<i>n</i> = 21)						
Al	Surface	25	−0.22	0.34	−0.67	0.51
Al	Subsurface	24	−0.86	0.53	−1.62	0.12
Ba	Surface	25	−0.36	0.39	−0.92	0.37
Ba	Subsurface	24	−0.55	0.46	−1.21	0.24
Fe	Surface	25	0.06	0.31	0.19	0.85
Fe	Subsurface	24	−0.02	0.44	−0.05	0.96
Pb	Surface	25	−0.02	0.52	−0.04	0.97
Pb	Subsurface	24	0.10	0.43	0.24	0.81
Sr	Surface	25	−0.33	0.32	−1.04	0.31
Sr	Subsurface	24	−0.18	0.36	−0.49	0.63
Juice (<i>n</i> = 7)						
Al	Surface	7	−0.13	0.33	−0.42	0.69
Al	Subsurface	7	−0.21	0.81	−0.26	0.81
Ba	Surface	7	0.18	0.38	0.47	0.66
Ba	Subsurface	7	0.55	0.38	1.45	0.21
Fe	Surface	7	0.06	0.30	0.19	0.86
Fe	Subsurface	7	0.27	0.49	0.55	0.61
Pb	Surface	7	−0.16	1.09	−0.14	0.89
Pb	Subsurface	7	0.10	0.76	0.13	0.90
Sr	Surface	7	−0.17	0.28	−0.60	0.57
Sr	Subsurface	7	−0.15	0.32	−0.48	0.65

Notes: The elements presented coincide with Table 1 as the elements with concentrations in soapberry leaves and berries that had significant relationships with covariates in the spatial regression models.

deposition. The research showed that six metals (Al, Ba, Cu, Fe, Pb, and Sr) had elevated concentrations in soapberry near the mine compared to farther away, and there was no correspondence between soapberry and soil metal concentrations,

suggesting that the elevated concentrations in soapberry were due to dust deposition onto leaves rather than uptake from local soils. The lichen biomonitoring study (currently in preparation) showed similar patterns for the same six

Table 3. Statistical values and percent concentration reductions after washing of the six metals that had elevated concentrations in soapberry leaves and berries, as determined through paired *t*-tests.

Element	Leaves					Berries				
	Ratio	<i>T</i>	<i>P</i>	df	Percentage reduction	Ratio	<i>T</i>	<i>P</i>	df	Percentage reduction
Al	0.73	12.83	<0.01	43	−27.1	0.52	4.66	<0.01	21	−47.9
Ba	0.99	0.62	0.54	43	−0.8	0.83	3.84	<0.01	21	−17.1
Cu	0.86	7.2	<0.01	43	−14.5	0.80	5.59	<0.01	21	−20.2
Fe	0.79	11.2	<0.01	43	−20.9	0.73	4.08	<0.01	21	−27.2
Pb	0.76	6.43	<0.01	43	−24.3	0.72	2.67	0.01	21	−27.9
Sr	1	0.01	0.99	43	0	0.87	3.54	<0.01	21	−13.3

metals. The effect in this study was most pronounced for copper and iron concentrations in leaves, which decreased with increasing distance from the mine and were statistically higher in certain threshold areas within the mine study area than in the reference area. Despite these results, a review of the literature showed that elevated metal concentrations in the samples near the mine area are low from a plant, animal, and human health perspective (Tables 4–6). These findings are summarized in the following discussion, with a focus on copper, iron, and aluminum. Note that this summary is not a health risk assessment; further work would need to be done to address human health risks with respect to consumption of traditional foods in the mine study area.

Copper

Copper concentrations in the mine study area were elevated, mainly in the threshold area directly around the mine and to the northeast, but not to levels that are generally toxic to plants.

For instance, the averages of leaf copper concentrations in the threshold area (14.6 ± 11.5 mg/kg) and the remainder of the mine study area (7.5 ± 4.6 mg/kg) were high relative to the range of concentrations in the reference area (3.7–7.2 mg/kg), but were within the range that copper is generally required by plant tissues for nutrition and growth (5–30 mg/kg) (Kabata-Pendias 2011). Copper deficiency in plants generally occurs when levels drop below 4 mg/kg, whereas phytotoxicity of copper begins to occur within the range of 20–100+ mg/kg (Adriano 2001). Compared to literature for other woody species, the averages for the threshold and mine study areas were below the average copper content in blueberry leaves from contaminated areas near smelting operations in Sudbury (75 mg/kg) (Whitby et al. 1976), as well as below leaf copper concentrations of woody species near copper mining operations in Sarcheshmeh, Iran, including *Elaeagnus angustifolia* (22–25 mg/kg) and various Rosaceae species (32–143 mg/kg) (Ghaderian and Ravandi 2012). Relative to uncontaminated

Table 4. Minimum and maximum concentrations of the six metals that had elevated concentrations in soapberry leaves and berries in the mine study area.

Metal	Leaves (mg/kg), <i>n</i> = 50		Berries (mg/kg), <i>n</i> = 21		Tea (µg/L), <i>n</i> = 19		Juice (µg/L), <i>n</i> = 7	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Al	19	272	1.5	37	36	159	788	7850
Ba	4.7	51	0.4	4.2	11	34	194	425
Cu	2.9	67.9	1.4	8.6	14	90	535	854
Fe	53	477	7.3	60	51	284	2500	7820
Pb	0.02	1.1	0.01	0.05	0.5	0.9	1.1	3.3
Sr	8.9	85	0.5	6.8	17	68	265	672

Notes: Means are not presented because the mine study area is a changing geospatial surface (i.e., not spatially homogenous) relative to element concentrations.

Table 5. Mean ($\pm$ standard deviation) and maximum concentrations in the reference area for the six metals that had elevated concentrations in soapberry leaves and berries in the mine study area.

Metal	Leaves (mg/kg), $n = 13$		Berries (mg/kg), $n = 6$		Tea ($\mu\text{g/L}$), $n = 5$		Juice ($\mu\text{g/L}$), $n = 2$	
	Mean $\pm$ SD	Max.	Mean $\pm$ SD	Max.	Mean $\pm$ SD	Max.	Min.	Max.
Al	42 $\pm$ 35	145	1.4 $\pm$ 0.4	2.0	52 $\pm$ 29	101	749	2840
Ba	17 $\pm$ 9	36	0.9 $\pm$ 0.4	1.5	23 $\pm$ 4	26	226	249
Cu	5.5 $\pm$ 1.0	7.2	1.8 $\pm$ 0.3	2.1	19 $\pm$ 9	33	313	500
Fe	109 $\pm$ 67	296	10 $\pm$ 2	12	90 $\pm$ 56	183	2205	6090
Pb	0.05 $\pm$ 0.05	0.20	0.007 $\pm$ 0.003	0.01	0.55 $\pm$ 0.05	0.62	1.1	1.5
Sr	20 $\pm$ 10	38	0.9 $\pm$ 0.4	1.4	18 $\pm$ 5	24.2	175	259

Notes: In contrast to Table 3, means are presented because the reference area is spatially homogenous relative to element concentrations.

Table 6. Concentration ranges and limits with regard to plant, animal, and human health. Ranges and limits for plants are based on Kabata-Pendias (2011) and Adriano (2001).

Metal	Baseline concentrations in plants		MTLs for animals (mg/kg)	Concentrations relative to human health	
	Sufficient or normal (mg/kg)	Excessive or toxic (mg/kg)		MAC ($\mu\text{g/L}$)	Avg. dietary intake (mg/day)
Al	7–3470	—	1000	2900	10†
Ba	1–180	500	100	2000	0.4–0.7‡
Cr	1–5	5–500	100–3000	50	0.002§
Cu	5–30	20–100	15–2000¶	2000	0.91–2.24#
Fe	160–330	1000	500–3000	—	18
Pb	5–10	30–300	45–250††	5	0.007‡‡
Sr	1.5–662§§	—	1000–2000	7000	1.3–1.9

Notes: Maximum tolerable levels (MTL) for animals are based on NRC (2005). Maximum acceptable concentrations (MAC) in drinking water for humans and estimates of approximate dietary intake are based on nine Health Canada technical reports from and 1987, 2016, 2019a, 2019b, 2019c, 2020, 2021.

† This estimate is based on a 70-kg adult and an intake of 143 $\mu\text{g/kg}$ body weight (bw) per day (Health Canada 2021).

‡ This range is based on a 70-kg adult taking in an estimate of 5.1–10.1 $\mu\text{g Ba/kg}$ bw per day (Health Canada 2020).

§ This estimate is based on a 70-kg adult with an intake of 0.023 $\mu\text{g Cr(VI)/kg}$ bw per day (Health Canada 2016).

¶ This range includes 15–40 mg/kg for ruminants and 100–2000 mg/kg for nonruminants (NRC 2005).

This range is based on the average daily exposure for a 70-kg adult over 20 yr of age (Health Canada 2019a).

|| Health Canada has not set a MAC for iron because there is little evidence to indicate that concentrations of iron commonly present in food or drinking water constitute any hazard to human health (Health Canada 1987). However, the Food and Nutrition Board of the Institute of Medicine of the National Academies has set an upper limit of 70 mg Fe/day (NRC 2005).

†† The limit for chickens and quail is 100 mg/kg when dietary Ca is high, but these animals can only tolerate 0.5–1.0 mg Pb/kg when Ca is low (NRC 2005).

‡‡ This value is based on a 70-kg adult taking in an estimate of 0.1 $\mu\text{g Pb/kg}$ body weight (bw) per day (Health Canada 2019b).

§§ Sr content in plants is lowest in grains (1.5–2.5 mg/kg) and highest in vegetable leaves (45–74 mg/kg) and legume tops (219–662 mg/kg). In blueberries, Sr ranges between 2.9 and 5.5 mg/kg. In soapberry berries, Sr content was reported at 0.7 mg/kg for an uncontaminated area near Bella Coola River, BC (Kuhnlein 1989).

sites, the threshold area was high compared to copper concentrations in leaves and stems of woody species of the Ericaceae family, including bilberry (4.5–8.0 mg/kg) and mountain cranberry (3.1–8.2 mg/kg) (Berthelsen et al. 1995), and species of the Arctostaphylos, Calluna, Empetrum, and Vaccinium genera (2.7–11 mg/kg) (Gjengedal et al. 2015). We could not find comparable data in the literature specifically for soapberry.

Regarding human health, copper concentrations in berries, tea, and juice were within acceptable limits. Copper is essential for human metabolism and the recommended daily dietary intake of copper is 2 mg/day for adults, most of which is ingested through food. In the mine study area, the ranges of copper concentrations for tea (14–90 $\mu\text{g/L}$) and juice (535–854 $\mu\text{g/L}$) were under Health Canada's guidelines on the

maximum acceptable concentration (MAC) for copper in drinking water (2000 µg/L) (Health Canada 2019a). For berries, the range of copper concentrations (1.4–8.6 mg/kg) were comparable to mean levels listed for whole cereal grains (4–6 mg/kg), root vegetables, nuts and fruits (<10 mg/kg), and animal products (2–4 mg/kg) (Adriano 2001). The average concentration (2.4 ± 1.5 mg/kg) for berries was higher than copper in soapberry berries collected near Dease Lake, BC (maximum 0.02–1.12 mg/kg) (RTEC 2010), but it was similar to soapberry berries collected near Bella Coola River, BC (3 mg/kg) (Kuhnlein 1989). Both sites were uncontaminated by metals and not naturally elevated in copper. The average concentration was also similar to the concentration reported for unwashed cranberries, lingonberries, and blueberries (3.1 ± 0.9 mg/kg) collected near oil sands facilities in northern Alberta (Stachiw et al. 2019).

Iron

Iron concentrations near the mine were moderately elevated, particularly in a very small rim around part of the tailings facility, but not enough to cause harm to plants. Iron is essential to biological function and deficiency is often more problematic in plants than toxicity, which can occur following iron accumulation above 1000 mg/kg (Kabata-Pendias 2011). The range in leaf iron concentrations from the mine study area (53–477 mg/kg) were high relative to edible parts of vegetables and some cereal grains (30–100 mg/kg), but they were within normal ranges reported for tissues of fodder plants (18–1000 mg/kg) (Kabata-Pendias 2011).

For humans, the Food and Nutrition Board of the Institute of Medicine of the National Academies has listed an upper limit of 70 mg Fe/day (NRC 2005). To reach this level, a person would need to consume 1.2 kg (~11 cups) of berries a day from the most iron-rich location in the mine study area (60 mg/kg), or 3.8 kg of berries a day from a location with average iron concentration (18.4 ± 15.1 mg/kg). This level of consumption is highly unlikely; local people consume at most a few cups of berries per day though typically much less because soapberry is usually consumed as juice concentrate mixed with water or in a confection. The average for berries was above the iron content of soapberry berries

collected in an uncontaminated area near Bella Coola River, BC (5 mg/kg) (Kuhnlein 1989), and of a range of wild berries collected in remote sites in northern Alberta (11–13 mg/kg) (Shotyk 2020), but it was below the mean iron concentrations of most foods (e.g., cereals 29.5 mg/kg; meat 26.2 mg/kg) (Health Canada 1987).

Aluminum

Aluminum concentrations in the mine study area were elevated in berries (not leaves) (Table 1), though average concentrations in berries (7.6 ± 9.1 mg/kg) were within normal ranges with respect to animal and human health (Table 6). The maximum aluminum concentration in berries near the mine site (37.1 mg/kg) was similar to the average concentration reported for berries (35 ± 21 mg/kg) collected near oil sand facilities in northern Alberta (Stachiw et al. 2019), but higher than concentrations of berries collected in remote sites in northern Alberta (11–20 mg/kg) (Shotyk 2020). The maximum concentration was within the range of average background values of various plant bulbs, tubers, and fruits (e.g., 7.2–76 mg/kg) (Kabata-Pendias 2011). To reach Health Canada's (2021) estimated average dietary intake of 10 mg/day (Table 6), a 70-kg person would need to consume 0.27 kg (~2.5 cups) of berries a day from the most aluminum-rich location near the mine site (37.1 mg/kg), which is a level of consumption that is unrealistic, as described above for iron.

For juice, the average concentration (2.6 ± 2.4 mg/L) from samples in the mine study area was within Health Canada's (2019) recently proposed MAC for total aluminum in drinking water of 2.9 mg/L. This MAC was exceeded by the aluminum concentration in a juice sample made from berries collected near the mine site (7.9 mg/L; Table 4), though a person would need to consume around 0.37 L (~1.5 cups) of juice concentrate a day from the aluminum-rich site to reach the MAC of 2.9 mg/L. This level of consumption is unrealistic; soapberry juice or concentrate is typically diluted prior to consumption and only a small amount (a tablespoon or so) is consumed per day primarily for medicinal purposes.

Other metals

Concentrations of the other three metals (Ba, Pb, and Sr) in the mine study area were within or

below baseline ranges and upper limits reported in the literature as safe with respect to plant and human health (Table 6). Of the three metals, lead is of greatest concern in terms of human health and potential toxicity, though it was only weakly detectable in leaves and berries with respect to the relationship between concentration and distance (Table 1), and the concentrations were within common ranges for human consumption. The average lead concentration in berries ($13.5 \pm 10.3 \mu\text{g/kg}$) was higher than concentrations of berries collected in remote sites in northern Alberta ($3\text{--}8 \mu\text{g/kg}$) (Shotyk 2020) and similar to the mean concentration reported for berries ($11 \pm 8.4 \mu\text{g/kg}$) collected near oil sands facilities in northern Alberta (Stachiw et al. 2019). The average was also comparable to lead in soapberry berries collected near Dease Lake, BC (maximum $10\text{--}25 \text{ mg/kg}$) (RTEC 2010). To reach Health Canada's (2019b) estimated daily intake of $7 \mu\text{g/kg}$ (Table 6), a 70-kg person would need to consume around 0.52 kg (~5 cups) of berries a day from a location with average concentration ($13.5 \mu\text{g/kg}$), or roughly 0.15 kg (~1.3 cups) per day from the location with the maximum concentration ($47.9 \mu\text{g/kg}$), which is a level of consumption that is unrealistic. Finally, the maximum concentrations in tea ($0.89 \mu\text{g/L}$) and juice ($3.52 \mu\text{g/L}$) were under the MAC for lead ($5 \mu\text{g/L}$) (Table 4).

CONCLUSIONS

Surface mines can be significant sources of dust containing metal contaminants, and it is important to understand the spatial extent of the dust and its potential effects on surrounding ecosystems and local communities. This study helped to address long-standing community concerns about the magnitude and distribution of mining dust deposition, particularly regarding where community members harvest traditional foods in the region. The study showed that six metals had elevated concentrations near the mine, though concentrations were generally low relative to health guidelines reported in the literature. Results also showed that washing leaves and berries can reduce metal concentrations by roughly 13–48%, depending on the metal.

This study applied a unique sampling approach by following the guidance shared by Nlaka'pamux members with respect to the harvest of leaves and berries, and the preparation of tea and juice. We acknowledge the potential contamination risks associated with this approach, including possible contribution of trace metals (particularly in the tea and juice samples) by glass canning jars, the coffee mill, stainless-steel colander, and filter paper, etc. However, a key focus of this research was to collaborate with local communities and to examine the types of soapberry foods and medicines that members may be consuming if they harvest in the area. We anticipated the potential for contamination, though we expect that we were still able to capture the dominant deposition patterns through analysis of leaves and berries. In subsequent studies, now that we better understand the dust deposition patterns related to soapberry, we would more specifically address the various sources of contamination to determine the proportion of elevated element concentration related to mining dust.

This study illustrates a model with global relevance for how mines can work with communities to address complex social–ecological problems. Our key management recommendations based on this work are as follows: (1) be flexible when designing fugitive dust studies and consider collaborating with local communities to identify a biological indicator that addresses their concerns; (2) consider building the study into a longer-term monitoring program in which a sub-set of sample sites would be revisited every five years or so to assess if dust mitigations are making measurable differences; and (3) consider pairing the study with a food safety or human health assessment to better address human health risks.

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