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Evaluation of metal aerosols in four communities adjacent to metal recyclers in Houston, Texas, USA

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Abstract

The metal recycling industry provides jobs, generates revenue in local communities and conserves energy and resources. Nonetheless, possible negative impacts of metal recyclers (MRs) include the potential for emissions of metal aerosols and other dusts, noise, traffic and fire during operations. In Houston, Texas, there were more than 180 resident complaints about air quality related to MRs from 2006 to 2011 that were reported to the city's 311 call system. As a part of a community-based participatory research study, Metal Air Pollution Partnership Solutions (MAPPS), we evaluated the impact of metal emissions from MRs on air quality over two years in four environmental justice communities. We simultaneously collected samples of inhalable particles (aerodynamic particle size less than 10 μm, PM_{10}) using a sampling strategy to capture emissions from the MRs while they were in operation at four locations within each community: an upwind location, the fence line of MR and two downwind locations and analyzed the samples for 10 metals. The highest values of iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), arsenic (As) and chromium (Cr) were detected at the fence lines of MRs. The normalized ratios of these metals at near and far neighborhood locations were 0.01 to 0.64 and 0.01 to 0.34, respectively, as compared with the metals at the fence line. The concentrations of metals rapidly decreased by 57–70% within 100 meters and reached similar levels at upwind (background) locations at approximately 600 meters. After adjusting the measured data for wind direction, rain and operating hours, we

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calculated non-carcinogenic hazard index values and carcinogenic risks for adult residents from breathing metals emitted from the facilities. Estimated inhalation cancer risks ranged from 0.12 case to 24 cases in 1 million people and the hazard index values ranged from 0.04 to 11.

Implications: In Houston, Texas, residents complained about air quality related to metal recyclers from 2006 to 2011. Using a community-based participatory research method, metal emissions were characterized at four environmental justice communities. The results indicate that metal concentrations were the highest at the fence line and decreased by 57–70% within 100 meters and reached similar levels of background at 600 meters. After adjusting the measured data for meteorological parameters and operating hours, estimated inhalation cancer risks ranged from 0.12 cases to 24 cases in 1 million people and hazard index values ranged from 0.04 to 11.

In 2015, more than 20 million tons of ferrous and nonferrous metal were generated by the metal recycling industry in the United States (U.S.). The U.S. Census Bureau estimated 8,160 scrap recycling facilities operating in the U.S. and Texas ranked second with 672 facilities (US Census Bureau 2016). Of 672 recycling facilities in Texas, there are more than 130 metal recyclers in operation in Houston (Texas Department of Public Safety 2019). There are both positive and negative impacts of having metal recyclers (MRs) operating within neighborhoods. The benefits may include provision of jobs for local communities, increased revenues for local businesses (e.g., due to customers frequenting restaurants or grocery stores before or after visiting the metal recycler) and conservation of resources and energy by recycling metals. On the other hand, MRs may generate dust (metal aerosol), odor, fume, noise and traffic, and experience explosions and/or fires. The processes for breaking down metals include torch cutting, shearing, shredding or crushing and these operations are mainly performed in open spaces in the scrap yard. Hence, metal aerosols that are generated may be transported outside the MR where community exposures may occur. Especially, metal fumes and aerosols from torch cutting of scrap metals are a concern as they are potentially inhalable (Chang et al. 2013; Chuang et al. 2018). While the chemical content of the aerosol depends on the type of scrap metal being processed, fumes and aerosols from MRs are primarily iron (Fe), chromium (Cr), manganese (Mn) or nickel (Ni) (Manoli et al. 2017; Querol et al. 2007).

In Houston, some residential areas are located close to MRs and other industrial facilities, in part, due to no formal zoning (City of Houston Planning and Development 2020). From 2006 to 2011, the City of Houston through their 311 call system received more than 180 complaints from residents about air quality potentially related to MRs operating near their homes. In response to residents' complaints, the Houston Health Department (HHD) conducted air monitoring at the fence line of 25 MRs and found that concentrations of Fe, Mn, Ni and lead (Pb) in total suspended particles (TSP) were significantly higher than those at urban background sites such as public parks and community centers (Raun et al. 2013).

Given resident 311 calls, the HHD air monitoring campaign and the potential risks of acute or chronic metal exposures as they relate to cancer (IARC 1990) and neurodevelopmental (Haynes et al. 2018; Leonhard et al. 2019) and cardiovascular (Yang et al. 2019; Ye et al. 2018) outcomes, we designed and conducted a community-based participatory research (CBPR) study, Metal Air Pollution Partnership Solutions (MAPPS) (NIEHS

#R01ES023563) to evaluate and mitigate the impact of metal emissions from MRs in four environmental justice (EJ) communities in Houston, TX (Symanski et al. 2020). The purpose of this paper is to describe results from our 20-month air monitoring campaign where we simultaneously measured 7-hour concentrations of 10 metals in inhalable particle samples (aerodynamic particle size less than 10 μm, PM_{10}) at four sampling sites in each neighborhood, including the fence line, an upwind site and two downwind neighborhood sites, as well as our neighborhood-, location- and metal-specific inhalation risk assessment findings.

Materials and methods

Sampling locations

We based our selection of MRs in part on previous air monitoring data available from the Bureau of Pollution Control and Prevention (BPCP) of HHD at the start of the MAPPS project. MRs were excluded for consideration if they were close to another metal recycler or close to an industry emitting metals (e.g., a steel alloy or steel pipe manufacturing facility). After examining the surroundings of potential metal emission sources, an additional restriction required that we could deploy air samplers at four sites in line with a consistent wind direction trajectory (i.e., at upwind, fence line, near neighborhood and far neighborhood sites), and in open spaces with no trees, physical structures or other obstructions nearby that could create eddies or affect wind direction.

MR1 is located on the east side of Houston with residential houses on the north side and bayou or green space areas on the south, east and west sides. MR2 is located on the south side of Houston and has residential areas on the west side. It is surrounded by commercial and other industrial facilities (not related to metal emissions) on the north, east and south sides. MR3 is located on the north side of Houston with other commercial and industrial facilities (not metal emitting). Residential homes border the south side. MR4 is east of downtown Houston. Residential areas are located on the northwest side and commercial and nonmetal emission industrial facilities border all other directions. MR1 processes stainless steel; MR2 processes stainless steel and other steel alloys; MR3 mostly recycles mild steel and scrap metals from the oil and gas industry; and MR4 processes nonferrous metals.

Field sampling methods

From September 2015 to May 2017, we conducted an air sampling campaign on 63 days to evaluate the impact of metal aerosol emissions from MRs on air quality in four surrounding neighborhoods. We only conducted air sampling when the wind was forecasted to blow from the facility downwind into the neighborhood with less than ± 30 degrees around the deployment axis (Table 1) and if the chance of precipitation was 30% or less. We simultaneously collected PM_{10} air samples at the upwind, fence line, and near and far neighborhood locations on a given sampling day. Figure 1 shows sampling sites in all four communities. Because of our sampling strategy, the upwind site was viewed as largely being unaffected by activities of the MRs and, hence, served to capture background sources of metal aerosols while air monitoring was conducted. We sampled when the predominant wind direction was from (1) the Southwest for the MR1 community, (2) East-North-East for

the MR2 community, (3) North or South for the MR3 community, and (4) Southeast for the MR4 community. Table 1 shows the number of residents living within buffer zones for each community defined by the near and far neighborhood sampling sites, as well as their distances from the fence line, which varied to accommodate the placement of the air monitoring equipment.

On each sampling day, field personnel met in the morning at the BPCP of HHD at approximately 7:50 am to load 8 BGI PQ-200 Federal Reference Method air samplers (Mesa Labs, Lakewood, CO), four folding tables, 8 chairs and other necessary supplies onto transportation vehicles. The HHD's Mobile Ambient Air Monitoring Laboratory (MAAML), which is equipped with a weather station for monitoring real-time meteorological factors such as wind direction, wind speed, airborne temperature and relative humidity, was deployed at the fence line. Two-person teams were assigned to the other three sampling sites. Two BGI samplers were co-located at the fence line and one BGI sampler was located at each of the other sites. At each site, BGI samplers were placed on a table to allow for an inlet that was approximately 1.8 meters from the ground and were set up for a sampling duration of 7 hours (9:00 am–4:00 pm) with flow rates of 16.7 liters per minute (lpm). Sampling periods at all sites were the same as field staff synchronized when the samplers were turned on and off. The sampling hours were shorter than the operation hours of the MRs (approximately 8 hours/day for MR1, MR2 and MR3; 9 hours/day for MR4).

Field team pairs were responsible for recording sampling parameters onto chain of custody (COC) forms, including: sampling site (both address and geo-coordinates), start and end times, flow rate, total air volume sampled, ambient air temperature, relative humidity and weather conditions. COC forms were reviewed by field team leaders before and after sampling. In addition, each team recorded other pertinent observations such as vehicular traffic activity, changes in weather and any interactions with residents. Furthermore, in case residents asked about field activities, we provided staff with MAPPS flyers in both English and Spanish that provided information about the purpose of the study and contact information to address any questions or concerns.

Upon completion of sampling, sampling data from the BGI samplers were recorded on COC forms and notebook logs. We shut down BGI samplers around 4:00 pm; afterward, instruments, equipment and supplies were transported back to BPCP by 5:00 pm. The recorded sampling data of BGI samplers (e.g., flow rates, sampling time, ambient temperature and pressure) were also downloaded to a designated computer by BPCP. On the same day, we removed the collected filters from the BGI samplers and stored them at 4°C until metal analysis. All samples were analyzed within one month after collection.

From May 2016 onwards and following a decision made by the MAPPS Community Advisory Board (CAB) (comprised of residents and metal recyclers), we notified via e-mail on the morning of air monitoring the respective MR managers and residents who lived near the metal recyclers of sampling efforts. We also asked managers to provide information on major activities on each day of sampling (e.g., number of torch cutters and duration of torch cutting). The study was approved by UTHealth Committee for the Protection of Human Subjects (CPHS).

Analytical methods

The collected filters were sent to the A&B Labs (Houston, TX), which has been certified by the American Industrial Hygiene Association (AIHA), for metal analysis. The lab used EPA method SW846–6020A (EPA, 1998) for analysis of 10 metals (arsenic (As), cadmium (Cd), Cr, cobalt (Co), Fe, Pb, Mn, Ni, selenium (Se) and silver (Ag)) using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). In brief, the metals collected on the filters were digested in trace metal free acid and then the digested solutions were diluted with ultrapure de-ionized water and analyzed by ICP-MS for each metal of interest. Metal concentrations on collected filters were adjusted for metals on field blank filters. Metal concentrations of field blanks were between 0.57 μg/filter (Fe) and 0.005 μg/filter (Ag). The limit of quantification (LOQ) for 10 metals was reported by the A&B Labs (Houston, TX). Assuming 7.01 m^3 of sampling volume for a 7-hr sampling duration, the LOQs were 77.8 ng/m^3 (Fe), 1.13 ng/m^3 (Mn), 2.51 ng/m^3 (Ni), 0.81 ng/m^3 (Pb), 0.91 ng/m^3 (As), 8.68 ng/m^3 (Cr), 0.74 ng/m^3 (Ag), 0.79 ng/m^3 (Cd), 1.97 ng/m^3 (Co) and 3.58 ng/m^3 (Se). Concentrations of four metals (Fe, Mn, Ni and Pb) were above LOQs; all samples except one were above LOQs for Cr. The rest of the metals had relatively high proportions of samples below LOQs: As (80%), Ag (70%), Cd (73%), Co (40%) and Se (37%). The values below LOQs were replaced by LOQ/2.

Data analysis

For each sampling day, we reviewed sampling times, flow rates, total sample volumes, wind direction and speed and metal concentrations on filters and blank filters. Samples were considered valid if they met the following criteria: the errors in the average flow rate during the sampling time were less than 2% and the differences in sampling volumes at the four sites on each sampling day were less than 5%. Fifty-nine out of 63 sampling days (94%) met these criteria. In addition, we deployed a pair of BGI samplers at the fence line for 26 sampling days to determine the accuracy of sampling and analytical methods. The precision in measuring all metals except Ag (25.1%) ranged from 11.7% (As) to 24.6% (Pb), satisfying the National Institute for Occupational Safety and Health accuracy criterion (Kennedy et al. 1995). As our focus was on estimating the impact of the metal recyclers on air quality, we subtracted upwind concentrations from measured values at the fence line and in the near and far neighborhood sites. We then examined the distributions of daily concentrations, by metal, neighborhood and the four sampling sites, and calculated means, medians, interquartile ranges (IQR), minimum and maximum values, geometric means (GM) and geometric standard deviations (GSD).

Data were not normally distributed; thus, we log-transformed concentrations for further statistical analysis. To compare the differences of each metal at the upwind locations across the four MRs, we used analysis of variance (ANOVA). To evaluate the impact of wind speed and distance from the fence line on metal concentrations in the near and far neighborhood sites, we conducted linear regression analysis using normalized values. For example, if concentrations of Fe were 2 $\mu g/m^3$; 1 $\mu g/m^3$; and 0.5 $\mu g/m^3$ at the fence line and in the near and far neighborhoods, respectively, then the normalized values were 1; 0.5; and 0.25. Multiple linear regression models were run for 6 metals (Fe, Mn, Ni, Pb, As and Cr), but not for Ag, Cd, Co or Se because large proportions of samples for these metals were below

LOQs. We also examined but did not detect interactions between wind speed and distance; thus, we report results from the regression models without an interaction term. We did not include the data provided from the metal recyclers on the days of sampling about operations (e.g., number of torch cutters) as potential determinants in regression models because this information was only obtained 8 months after sampling began and there was little variation in reported activities across days of sampling for any given MR. All statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC) and evaluated at a significance level of $\alpha = 0.05$.

Risk Assessment

Neighborhood-specific inhalation risk assessments were conducted using the U.S. EPA's framework and guidance methods (US EPA 2009). Carcinogenic risk and non-carcinogenic hazard estimates were calculated for adults over a lifetime (70 years) and assume metal exposures over 30 years at the levels that we measured in ambient air. Toxicity values for each metal were obtained from the EPA Regional Screening Levels (US EPA 2009). Inhalation Unit Risk (IUR) concentrations for As, Cd, Co and Ni were available for the cancer risk assessment and reference concentrations (RfC) for As, Cd, Co, Mn, Ni and Se for the noncancer hazard assessment (US EPA 2017). Metals without IUR or RfC values were not included in the risk assessments. Prior to conducting risk assessments, metal concentrations (already adjusted for background levels) were further adjusted downwards to account for MR operating days and hours, rainfall and wind direction to estimate annual ambient air levels of metals. For these adjustments, meteorological data were obtained from four air monitoring locations in the area for a two-year period (2014–2016) and hours of operation were obtained directly from the metal recyclers serving on the CAB. Risk estimates were calculated using the 95th upper confidence limit of the mean concentrations by metal and for all metals by site. The 95th upper confidence limit of the mean values were calculated using EPA's ProUCL recommended value (US EPA 2009). We used cut points between 1 in a million and 1 in 100,000 to gauge potential cancer risks and a cut point of 1 for hazard quotient (HQ) and hazard index (HI) values (US EPA 2009).

Results and discussion

When classified by season, nearly equal numbers of samples were collected during the warm (May-Oct) (n = 32) and cool (Nov-Apr) (n = 31) seasons: MR1 – 9 samples in the warm season and 5 in the cool season; MR2 – 7 samples were collected in each season; MR3 – 11 samples were collected during the warm season and 10 in the cool season; and MR4 – 5 samples were collected during the warm and 9 in the cool season. A sampling pump failed on four days (two days in the MR1 community and two days in the MR4 community). Thus, data collected on 12 (MR1 and MR4), 14 (MR2) and 21 (MR3) days contributed to the analyses (n = 59 days).

Upwind sites

Because our sampling strategy was limited to days when the wind predominantly blew downwind from the MRs into the neighborhood, we considered upwind sites as representative of background levels when monitoring took place. The average background

concentrations of seven metals (Cd, Cr, Co, Fe, Mn, Ni and Pb) across neighborhoods were not significantly different ($p > .05$). For Fe, mean concentrations at the upwind locations ranged from 0.66 (MR4) to 1.01 (MR1) μg/m^3 ($p = .571$) (GMs ranged between 0.42 and 0.78 μg/m^3). In contrast, upwind concentrations of Ag, As and Se were significantly different among the four neighborhoods. The mean concentrations of Ag ranged from 0.53 (MRs 1, 2 and 4) to 3.06 (MR3) ng/m^3 ($p = .003$); mean concentrations of As ranged from 0.54 (MR4) to 1.22 (MR2) ng/m^3 ($p = .002$) (GMs between 0.43 and 1.15 ng/m^3); and mean concentrations of Se ranged from 0.63 (MR4) to 1.59 (MR2) ng/m^3 ($p = .002$).

Our results showed that seven metals (Fe, Mn, Ni, Pb, Cd, Co and Cr) at upwind sites were significantly lower than those at the fence line of MRs and that concentrations of three metals (Ag, As and Se) were similar at both sites. Thus, the Ag, As and Se that we measured in air samples at the upwind and fence line sites were likely due to sources other than the MRs. Ag, which was only detected on less than 20% of collected filters, is likely from resuspended dust or from industrial operations handling silver. Coal power plant emissions are a major source of As and Se in ambient air (Hammond et al. 2008; Thurston, Ito, and Lall 2011; Tunno et al. 2016) as is road dust from traffic emissions for As (Balakrishna, Pervez, and Bisht 2011; Pancras et al. 2013).

Fence line sites

We examined the fence line profiles of all metals of each facility (Table 2). Fe was the most dominant species at all MRs, consisting of 90 to 94% of the total concentration of all metals combined. Mean concentrations of Fe were the highest at MR2 (mean = 15.94 μg/m^3 and GM = 14.52 μg/m^3) followed by MR3 (mean = 13.21 μg/m^3 or GM = 8.45 μg/m^3), MR1 (mean = 5.57 μg/m^3, or GM = 2.47 μg/m^3) and MR4 (mean = 2.04 μg/m^3 or GM = 1.81 μg/m^3). The concentration of Fe at the fence line of MR2 was about 8 times greater than MR4.

Figure 2 shows the sum of the mean concentrations of 9 metals by metal recycler. We excluded Fe in Figure 2 when summing total metal concentrations in our air samples because scrap metals (steel or stainless-steel alloys) primarily contain greater than 90% of Fe. The sum of the concentrations of 9 metals at MR2 was the highest (1,587 ng/m^3) whereas that at MR4 was the lowest (113 ng/m^3). The summed concentration at MR2 was approximately 14, 7 and 3 times higher than those at MR4, MR1 and MR3, respectively. We found Ni, Cr, Mn and Pb contributed approximately 97% to the overall sum of the 9 metals combined. Ni was the primary component at both MR1 and MR2; Mn was the primary component at MR3 and Pb was the primary component at MR4 (although the concentrations were lower than those from MR2 and MR3).

Figure 3 shows the mean metal concentrations at the fence line by MR. MR1 and MR2 had similar profiles of five metals (Fe > Ni > Mn > Cr > Pb) whereas MR3 and MR4 had a different metal profile (Fe > Mn > Pb > Ni > Cr) (Figure 3a). The mean concentrations of Fe, Mn, Ni and Cr were the highest at MR2 followed by MR1 and MR3. The mean concentration of Pb was the highest at MR3 followed by MR2, MR4 and MR1. There were fewer clear patterns in fence line concentrations of As, Co, Ag, Se and Cd across the four MRs (see Figure 3b).

Our results suggest that Fe, Ni, Cr, Mn and Pb were the predominant metals present in MR emissions. Although these five metals were mostly present at the fence line of all MRs, their relative contributions to summed concentrations of all metals varied, which was likely due to differences by MR in terms of which scrap metals they accept and how scrap metals are processed. For instance, in summing the measured concentrations of all metals except Fe, Mn predominated at MR3 (54.5%) whereas the contribution of Mn was lower at the other facilities (21.5–29.7%) (suggesting that MR3 processed scrap metals rich in Fe-Mn). On the other hand, MR1 and MR2 likely processed scrap metals rich in Fe-Ni-Cr-Mn and MR4 likely processed scrap metal rich in Fe-Pb-Mn-Ni. Not only did the profiles of metals differ but our data suggest that emission volumes varied as well.

Near and far neighborhood sites

Figure 4 shows that the normalized ratios for six metals (Fe, Mn, Ni, Pb, As and Cr) where each data point represents the average normalized ratios after adjusting for background (upwind) sites over four MRs. The normalized ratios of six metals (Fe, Mn, Ni, Pb, As and Cr) rapidly decreased from the fence lines by 57 – 70% within 100 meters and 83 – 91% within 200 meters. The normalized exponential curves for all six metals plateaued when the distance from the fence line was about 400 meters or greater. The model fit was good for all metals (R^2 ranged from 0.83–0.97) and the slopes of decay were similar across six metals (Fe: −0.0091; Mn: −0.0088; Ni:−0.0121; Pb: −0.0087; As: −0.0084; and Cr: −0.0089).

Table 3 shows the results from the multiple linear regression models between the normalized ratios for Fe, Mn, Ni, Pb, As and Cr and distance and wind speed. There was an effect of distance for Fe, Mn, Pb and Cr at all MRs. With a 100-meter distance from the fence line, ratios of Fe decreased 56%, 16%, 39% and 10% for MR1, MR3, MR2 and MR4, respectively. The normalized ratios of Pb at all MRs decreased from −14% (MR4) to −51% (MR1) with 100-meter distance from the fence line. For all metal recyclers except MR4, there was also an effect of distance for Ni and As. We did not find significant effects of wind speed except for As (MR1 and MR3) and Cr (MR1).

There was attenuation in ambient air levels of metals due to MR emissions with distance from the fence line. Metal concentrations decreased by 60% within 100 meters and an additional 20% between 100 and 200 meters. However, Fe and Mn decreased more rapidly with distance than did Ni, Pb, As and Cr. These differences might be due to differences in aerosol size distributions. It is likely that Fe and Mn emitted from MRs are larger size particles. Metals bound to particles greater than 1 μm could be suspended in the air for a relatively shorter time and thus reducing concentrations within 200 meters from the fence line because of a higher settling velocity as compared to metals bound to smaller particles (Cahill et al., 2016; Xia and Gao 2011). Also, at 600 meters from the fence line, metal concentrations reached concentrations measured at upwind locations. Thus, MRs appear to be a hyper-localized source of metal air pollution, potentially increasing exposures to metals for residents who live close by.

Meteorological conditions such as wind speed and direction can affect the dispersion of metal aerosols. In general, the association between particulate matter and wind speed is inverse (Hussein et al. 2006; Kim et al. 2015). Because we collected PM_{10} samples in

neighborhood sites on downwind days, we only examined association of wind speed and detected effects for As downwind from the fence lines.

Risk Assessment

We observed values of less than 1 in a million for cancer risks at all locations for MR4 (see Table 4). At the fence line of three metal recyclers (MR1, MR2 and MR3) where relatively few residents live (Table 1), cancer risks were 2.7, 23.7 and 3.3 per million, respectively. The risk was primarily attributed to Ni, Co and As (generally, Ni > Co > As). Risks were also above 1 in a million, but of lower magnitude than the fence line location, in the near neighborhoods for MR2 and MR3. Table 5 summarizes estimated increase in non-cancer hazards for adult residents by metal (HQ) and for the sum of metals combined (HI). At the fence line, the HIs were the highest at MR2 (11.3) followed by MR3 (1.6), MR1 (1.4) and MR4 (0.26). The contribution of Ni emissions on estimated values of HI at the fence line was 85% (MR1), 88% (MR2), 86% (MR3) and 58% (MR4). We observed HI values less than 1 at near and far neighborhood sites across all MRs.

The strengths of this study include simultaneous air sampling at four sites in the sampling neighborhoods. Previous studies have characterized profiles of metals data using stationary monitoring sites, possibly affected by multiple sources of metal emissions (Gonzalez et al. 2017; Manoli et al. 2017; Querol et al. 2007). However, in our study, we selected study locations with predominantly a single source of metal emissions (i.e., the MRs) and collected air samples when the predominant wind direction was from the MR toward the neighborhoods where our samplers were located. Moreover, because sampling was conducted only when the residential sites were directly affected by the metal aerosols emitted from MRs we were able to characterize the impact of MRs on outdoor air quality. Thus, we were able to identify differences between the fence line and upwind (background) sites for several signature metals (Fe, Mn, Ni, Pb and Cr). We also detected modest increases in health risks associated with metal emissions at some, but not all, MRs, mostly at the fence line that decreased in the near neighborhood location and fell to acceptable levels (i.e., risk less than 1 in a million for cancer and HI values less than 1 for noncancer) in the far neighborhood.

Conclusion

We collected metal aerosols at residential areas during periods when the outdoor air quality was predominantly affected by MRs which were used to estimate health risks among adult residents living in each sampling location. We confirmed that MRs during operations primarily emitted Fe, Mn, Ni, Cr and Pb but that they had different metal profiles. Ni was the major contributor of the health risks that we estimated. Our study also showed that concentration levels of metals rapidly decreased (81–91%) within 200 meters from the fence line and that metal concentrations at approximately 600 meters from the fence line of MRs were close to background levels. The health risk estimates displayed similar patterns. While risks, if they were elevated, were relatively modest, these findings coupled to community survey results have been used to develop a public health action plan that will be reported on

separately – including voluntary controls implemented by the metal recyclers – to improve environmental health in our MAPPS neighborhoods (Symanski et al. 2020).

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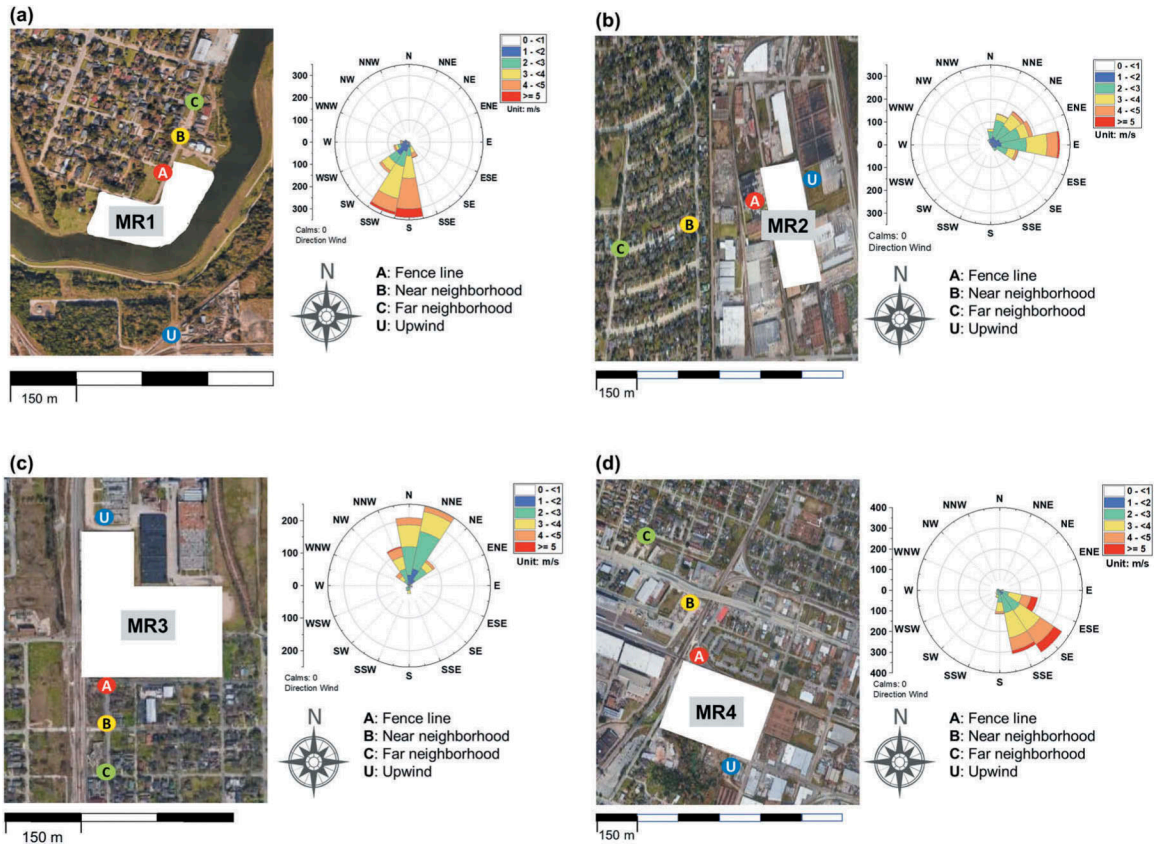

Figure 1.

Sampling locations (U, A, B, C) near metal recyclers (MRs) and wind directions recorded while metal aerosols were collected over seven hours at four MRs over entire sampling period (September 2015–May 2017). Wind rose direction confirmed that wind blew from upwind (U) location toward the MRs, fence line of MRs (A) and near (B) and far (C) neighborhood locations.

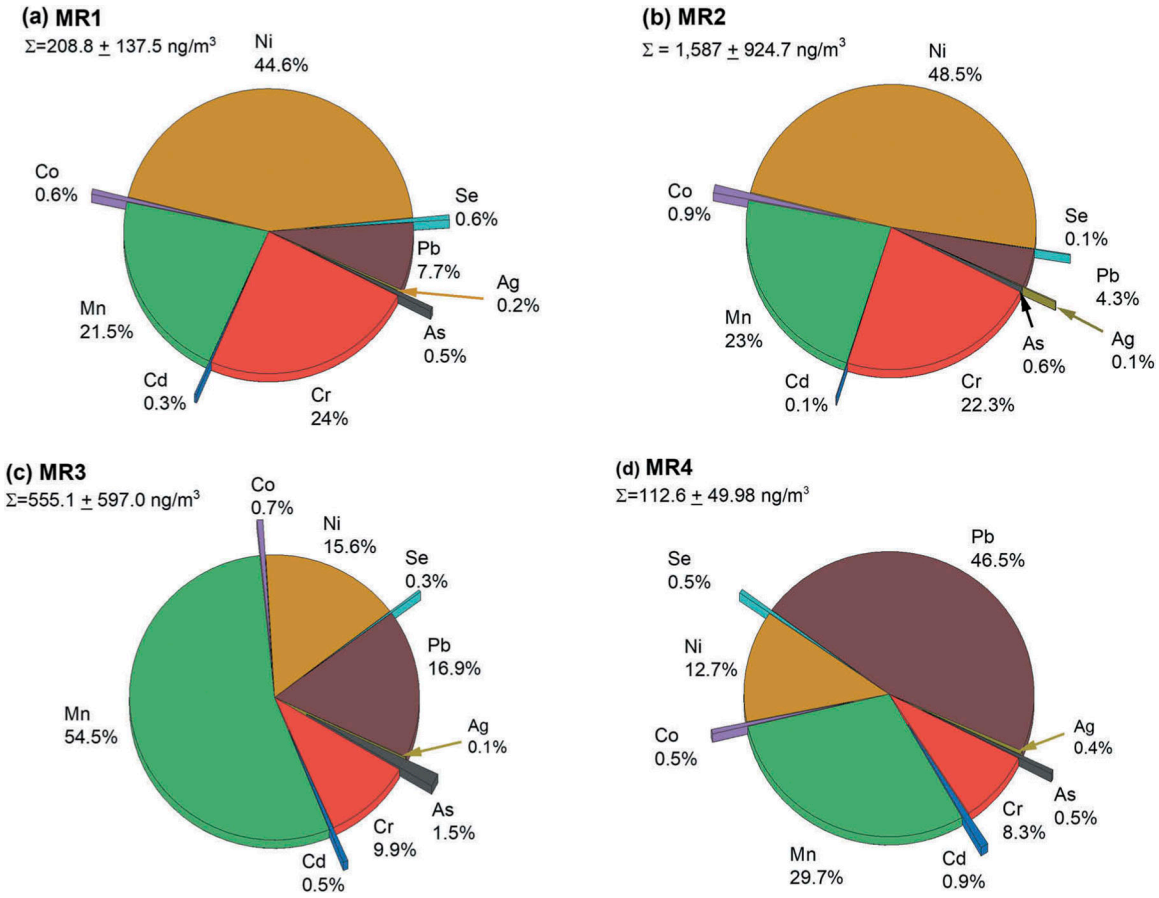

Figure 2.

Pie charts represent the contribution of each metal fraction to the sum of 9 metals emitted by each metal recycler (MR). Mean concentrations of the sum of 9 metals are shown under the title of each facility.

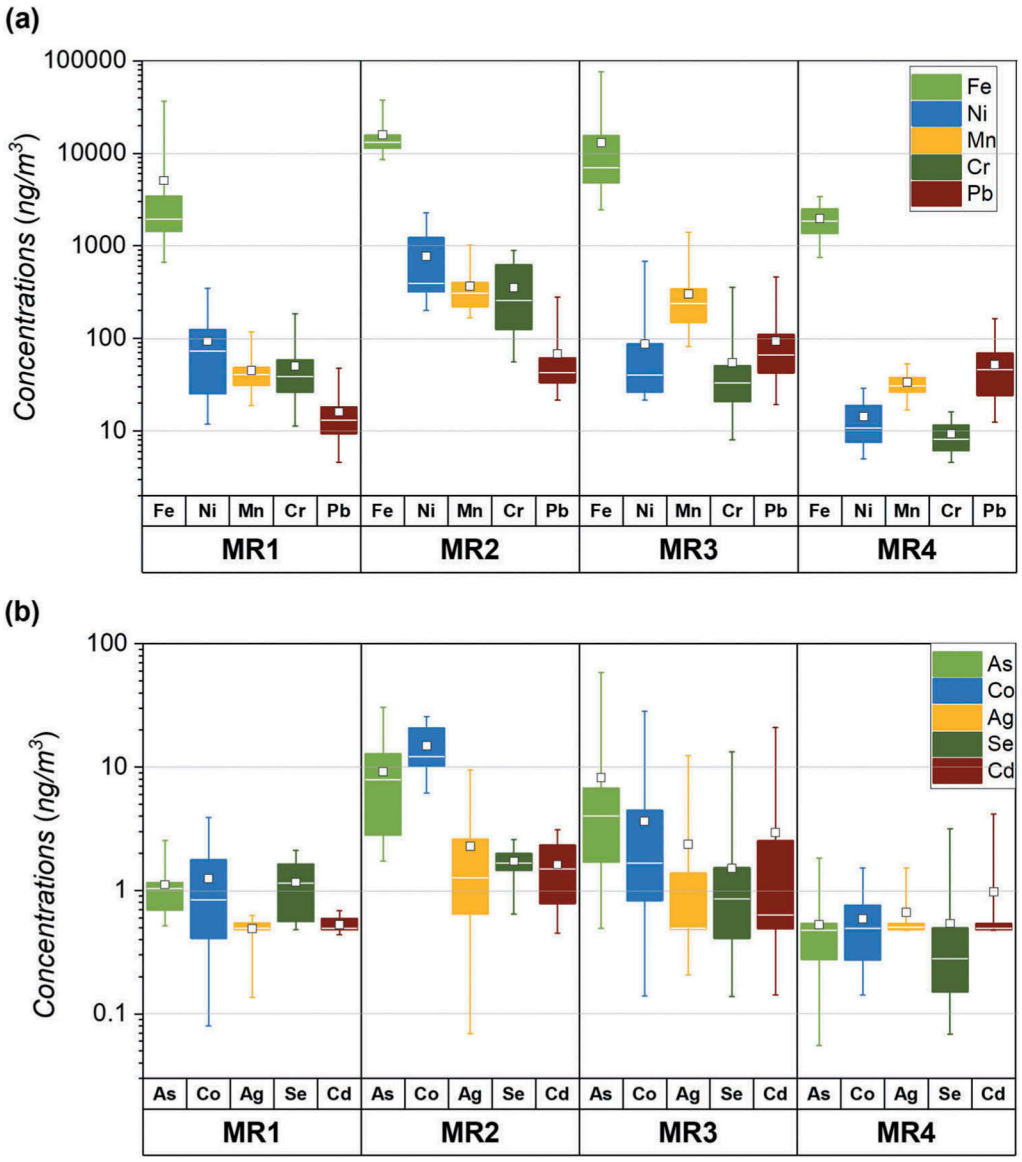

Figure 3.

Comparison of distribution of 10 inhalable metals at the fence lines of MRs over 7-hr sampling days. Open squares show the mean concentrations and the solid lines in the box show the median concentrations. Low and high bars represent minimum and maximum concentrations.

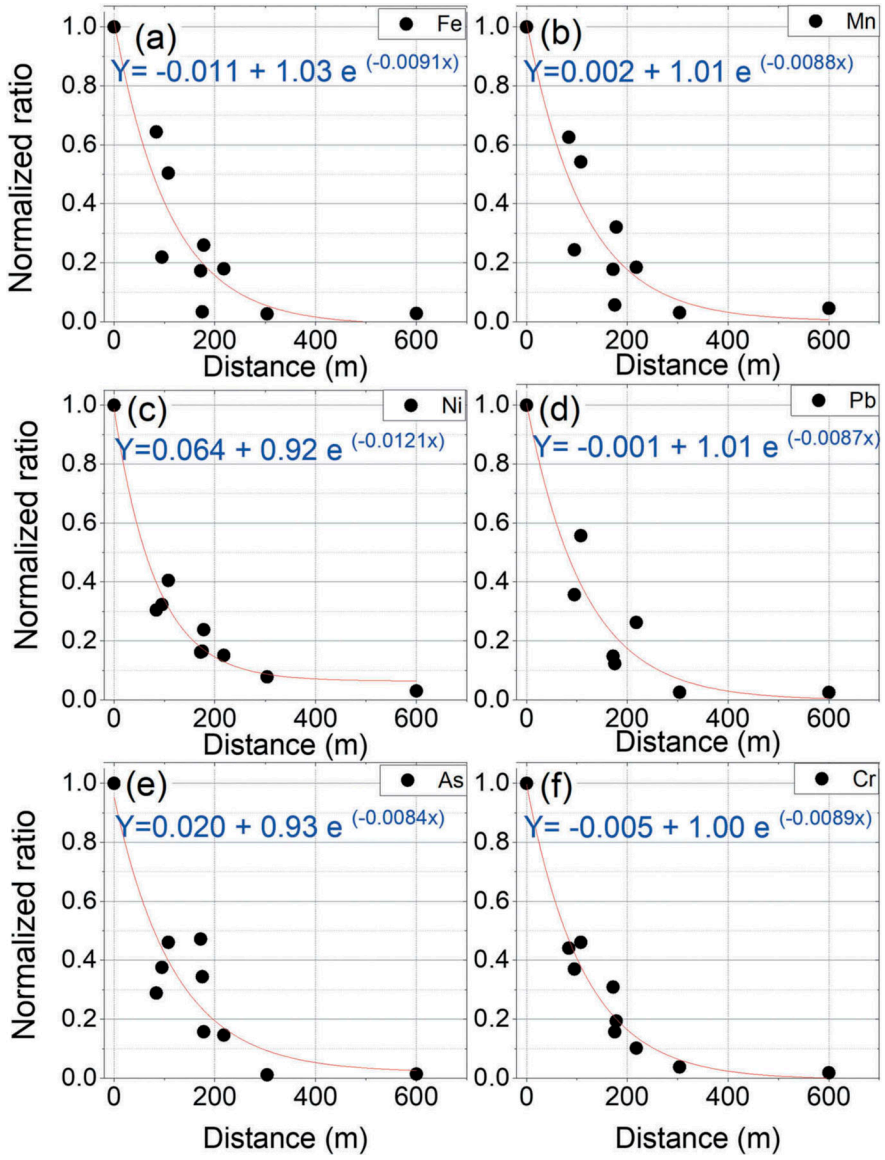

Figure 4.

Association between the normalized ratio of six metals (Fe, Mn, Ni, Pb, As, and Cr) and the distance from the fence line over four MRs.

Table 1.

Distances of the near (B) and far neighborhood (C) locations from the fence line (A) of the metal recyclers (MRs)*.

Facility	Distance of near neighborhood (B) from the fence line (A)	Estimated number of residents living within a buffer defined by (B)	Distance of far neighborhood (C) from the fence line (A)	Estimated number of residents living within a buffer defined by (C)
MR1	95 meters	65	175 meters	233
MR2	304 meters	438	600 meters	2,040
MR3	84 meters	146	178 meters	419
MR4	172 meters	329	557 meters	3,115

Notes. See Figure 1 for maps of the sampling locations for each MR.

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Table 2.

Mean concentrations of 10 metals at four different metal recyclers (MRs).

Metal	MR1 (n = 12)	MR2 (n = 14)	MR3 (n = 21)	MR4 (n = 12)
As	1.11 ± 0.58	9.18 ± 8.05	8.23 ±13.04	0.53 ± 0.47
Ag	0.49 ± 0.12	2.28 ± 2.67	2.36 ± 3.56	0.66 ± 0.34
Cd	0.53 ± 0.07	1.62 ± 0.89	2.95 ± 5.16	0.98 ± 1.14
Co	1.25 ± 1.23	14.85 ± 6.47	3.64 ± 6.04	0.59 ± 0.41
Cr	50.13 ± 46.12	354.6 ± 288.7	54.59 ± 74.6	9.35 ± 4.06
Fe	5091 ±10,058	15,869± 8070	13,144±16,585	1985 ±824.0
Mn	45.00 ± 24.95	365.7 ± 215.8	301.7 ± 280.7	33.43 ±10.85
Ni	93.09 ± 95.54	769.8 ± 668.6	86.53 ± 142.0	14.24 ± 7.98
Pb	16.05 ± 11.21	67.78 ± 69.71	93.51 ± 97.23	52.23 ±40.07
Se	1.17 ± 0.62	1.73 ± 0.48	1.51 ± 2.76	0.54 ± 0.81

Notes. Unit: ng/m^3

Concentrations are shown as Mean ± SD (standard deviation)

Table 3.

Effects of wind speed, distance from the fence line, and interactions of wind speed and distance from the fence line on six metals for each metal recycler (MR).

Metal	Parameters	MR1	MR2	MR3	MR4
Fe	Intercept	0.950 ± 0.116 ($p < .001$)	0.861 ± 0.152 ($p < .001$)	0.780 ± 0.149 ($p < .001$)	0.947 ± 0.286 ($p < .001$)
	Distance	**−0.560 ± 0.043 ($p < .001$)**	**−0.163 ± 0.0.015 ($p < .001$)**	**−0.385 ± 0.047 ($p < .001$)**	**−0.102 ± 0.029 ($p = .001$)**
	Wind speed	−0.008 ± 0.031 ($p = .791$)	−0.007 ± 0.051 ($p = .891$)	0.060 ± 0.040 ($p = .147$)	−0.060 ± 0.0.077 ($p = .440$)
	Overall R^2	0.852	0.753	0.582	0.308
Mn	Intercept	0.914 ± 0.099 ($p < .001$)	0.885 ± 0.141 ($p < .001$)	0.796 ± 0.133 ($p < .001$)	1.064 ± 0.335 ($p < .001$)
	Distance	**−0.547 ± 0.046 ($p < .001$)**	**−0.160 ± 0.015 ($p < .001$)**	**−0.371 ± 0.042 ($p < .001$)**	**−0.080 ± 0.033 ($p = .022$)**
	Wind speed	0.008 ± 0.034 ($p = .806$)	−0.016 ± 0.052 ($p = .753$)	0.055 ± 0.036 ($p = .135$)	−0.098 ± 0.091 ($p = .292$)
	Overall R^2	0.822	0.739	0.618	0.173
Ni	Intercept	0.811 ± 0.122 ($p < .001$)	0.814 ± 0.137 ($p < .001$)	0.908 ± 0.115 ($p < .001$)	0.550 ± 0.444 ($p = .225$)
	Distance	**−0.484 ± 0.045 ($p < .001$)**	**−0.163 ± 0.015 ($p < .001$)**	**−0.393 ± 0.036 ($p < .001$)**	−0.053 ± 0.044 ($p = .243$)
	Wind speed	0.036 ± 0.033 ($p = .283$)	0.001 ± 0.051 ($p = .988$)	−0.001 ± 0.031 ($p = .992$)	0.042 ± 0.122 ($p = .732$)
	Overall R^2	0.796	0.784	0.697	0.044
Pb	Intercept	0.776 ± 0.157 ($p < .001$)	0.840 ± 0.149 ($p < .001$)	0.634 ± 0.339 ($p = .067$)	0.805 ± 0.202 ($p < .001$)
	Distance	**−0.507 ± 0.057 ($p < .001$)**	**−0.148 ± 0.014 ($p < .001$)**	**−0.353 ± 0.107 ($p = .002$)**	**−0.139 ± 0.020 ($p < .001$)**
	Wind speed	0.051 ± 0.042 ($p = .231$)	0.001 ± 0.047 ($p = .985$)	0.120 ± 0.092 ($p = .199$)	−0.016 ± 0.055 ($p = .772$)
	Overall R^2	0.725	0.755	0.205	0.592
As	Intercept	1.594 ± 0.274 ($p < .001$)	0.858 ± 0.152 ($p < .001$)	1.121 ± 0.089 ($p < .001$)	1.027 ± 0.758 ($p = .196$)
	Distance	**−0.383 ± 0.125 ($p = .008$)**	**−0.165 ± 0.052 ($p < .001$)**	**−0.411 ± 0.028 ($p < .001$)**	−0.054 ± 0.076 ($p = .493$)
	Wind speed	**−0.209 ± 0.072 ($p = .011$)**	−0.007 ± 0.052 ($p = .895$)	**−0.063 ± 0.025 ($p = .015$)**	−0.060 ± 0.208 ($p = .778$)
	Overall R^2	0.543	0.752	0.825	0.037
Cr	Intercept	1.301 ± 0.172 ($p < .001$)	0.857 ± 0.144 ($p < .001$)	0.968 ± 0.097 ($p < .001$)	1.053 ± 0.405 ($p = .017$)
	Distance	**−0.487 ± 0.044 ($p < .001$)**	**−0.164 ± 0.014 ($p < .001$)**	**−0.4207 ± 0.031 ($p < .001$)**	**−0.093 ± 0.032 ($p = .008$)**
	Wind speed	**−0.097 ± 0.045 ($p = .041$)**	−0.003 ± 0.049 ($p = .944$)	−0.006 ± 0.026 ($p = .824$)	−0.074 ± 0.112 ($p = .517$)
	Overall R^2	0.826	0.770	0.788	0.304

Notes. Multiple linear regression analysis was performed with normalized ratios of metals as dependent variables. Wind speed (m/s) and distance from the fence line (m) were used as independent variable. Interaction terms between wind speed and distance from the fence line were not included due to insignificant effects for all models. an increase of 100-meter distance from the fence line decreases the slope estimate of distance with standard errors. an increase of 1 m/s of wind speed changes in the slope estimates with standard errors. Significant estimates and standard errors are shown with bold fonts.

Table 4.

Estimated increase in cancer risks for adult residents by sampling site from inhalation of metals (As, Cd, Co and Ni) emitted from each metal recycler.

		Cancer risk (cancer cases per million people)		
Facility	**Metals**	**Fence line**	**Near Neighborhood**	**Far Neighborhood**
MR1	As	0.12	0.04	0.06
	Cd	0.02	0.07	0
	Co	0.89	0.17	0.05
	Ni	1.7	0.64	0.32
	Total	**2.7**	**0.92**	**0.43**
MR2	As	2.3	0.02	0.03
	Cd	0.16	0	0
	Co	6.90	1.4	0.30
	Ni	14	0.85	0.31
	Total	**24**	**2.3**	**0.64**
MR3	As	0.68	0.36	0.20
	Cd	0.04	0	0
	Co	0.62	0.26	0.17
	Ni	2.0	1.1	0.47
	Total	**3.3**	**1.7**	**0.84**
MR4	As	0.07	0.02	0.27
	Cd	0.27	0	0
	Co	0.25	0.07	0.25
	Ni	0.21	0.03	0.21
	Total	**0.80**	**0.12**	**0.73**

Notes. Cancer risks estimates were calculated for adults over a lifetime (70 years) and assume metal exposures over 30 years.

Table 5.

Estimated increase in non-cancer hazard by sampling site for adult residents from inhalation of metals (As, Cd, Co, Mn, Ni and Se) emitted from each metal recycler.

		Hazard Quotient and Hazard Index for non-cancer diseases		
Facility	**Metals**	**Fence line**	**Near Neighborhood**	**Far Neighborhood**
MR1	As	0	0	0
	Cd	0	0.01	0
	Co	0.04	0.01	0
	Mn	0.17	0.13	0
	Ni	1.2 *	0.45	0.22
	Se	0	0	0
	Total	**1.4** *	**0.60**	**0.22**
MR2	As	0.08	0	0
	Cd	0.02	0	0
	Co	0.30	0.06	0.01
	Mn	0.90	0.03	0.04
	Ni	10 **	0.60	0.21
	Se	0	0	0
	Total	**11** **	**0.69**	**0.26**
MR3	As	0.03	0.01	0.01
	Cd	0.01	0	0
	Co	0.03	0.01	0.01
	Mn	0.16	0.05	0.03
	Ni	1.4 *	0.76	0.33
	Se	0	0	0
	Total	**1.6** *	**0.83**	**0.38**
MR4	As	0	0	0.01
	Cd	0.04	0	0
	Co	0.01	0	0.01
	Mn	0.06	0.02	0.03

		Hazard Quotient and Hazard Index for non-cancer diseases		
Facility	**Metals**	**Fence line**	**Near Neighborhood**	**Far Neighborhood**
	Ni	0.15	0.02	0.15
	Se	0	0	0
	Total	**0.26**	**0.04**	**0.20**

Notes.

*
HI Exceeds 1,

**
HI Exceeds 10

Noncancer risks estimates were calculated for adults and assume metal exposures over 30 years.