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ORIGINAL RESEARCH

The Global Burden of Lead Toxicity Attributable to Informal Used Lead-Acid Battery Sites

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Abstract

BACKGROUND Prior calculations of the burden of disease from environmental lead exposure in low- and middle-income countries (LMICs) have not included estimates of the burden from lead-contaminated sites because of a lack of exposure data, resulting in an underestimation of a serious public health problem.

OBJECTIVE We used publicly available statistics and detailed site assessment data to model the number of informal used lead-acid battery (ULAB) recyclers and the resulting exposures in 90 LMICs. We estimated blood lead levels (BLLs) using the US Environment Protection Agency's Integrated Exposure Uptake Biokinetic Model for Lead in Children and Adult Lead Model. Finally, we used data and algorithms generated by the World Health Organization to calculate the number of attributable disability adjusted life years (DALYs).

RESULTS We estimated that there are 10,599 to 29,241 informal ULAB processing sites where human health is at risk in the 90 countries we reviewed. We further estimated that 6 to 16.8 million people are exposed at these sites and calculate a geometric mean BLL for exposed children (0-4 years of age) of 31.15 µg/dL and a geometric mean BLL for adults of 21.2 µg/dL. We calculated that these exposures resulted in 127,248 to 1,612,476 DALYs in 2013.

CONCLUSIONS Informal ULAB processing is currently causing widespread lead poisoning in LMICs. There is an urgent need to identify and mitigate exposures at existing sites and to develop appropriate policy responses to minimize the creation of new sites.

KEY WORDS informal economy, lead poisoning, low- and middle-income countries, soil pollution, disability adjusted life years, recycling

INTRODUCTION

Contaminated soils at polluted "hot spots"—active and abandoned mines, smelters, industrial facilities, and chemical waste sites—threaten the environment and human health globally. In high-income countries (HICs), substantial progress has been made toward identifying and remediating hazardous waste sites and thus in reducing exposures and disease. In low- and medium-income countries (LMICs), by contrast, the extent and severity of soil contamination at these sites has not been adequately mapped or quantified.[1] Information on the burden of disease attributable to hazardous exposures at contaminated

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sites has not previously been available for inclusion in estimates of the global burden of disease by either the Institute for Health Metrics and Evaluation (IHME) or the World Health Organization (WHO).[2,3]

Toxic Sites Identification Program. To close the information gap regarding soil pollution at industrial hot spots in LMICs and its effects on human health, Pure Earth (PE; formerly Blacksmith Institute) launched the Toxic Sites Identification Program (TSIP) in 2008.[4]

The central element of TSIP is a protocol for rapid field-based identification and assessment of hazardous waste sites in LMICs. This protocol has been adapted from the standard source-pathway-receptor model for field assessment of toxic sites in use by the US Environmental Protection Agency (USEPA) and was specifically adjusted by PE to accommodate field application in LMICs by nonprofessional local investigators trained through the program.[5,6] At each site, environmental samples are collected, photographs are taken, and key characteristics are documented. Completed assessments are entered into an online database. To date 2591 sites in 49 countries have been assessed.

The basic approach is to identify a single key pollutant at each site. The key pollutant is the dominant contaminant at a site whose concentrations are most significantly elevated above relevant environmental standards. Lead, mercury, hexavalent chromium, and highly toxic environmentally persistent pesticides have been the key pollutants most commonly identified. Estimates of environmental contamination and disease burden are attributed solely to the key contaminant and not to any other hazardous materials that may be present at a site. This bias likely underestimates the true environmental burden of disease.

PE has collaborated with local partners and secured support from national and international funders to remediate some of the most hazardous sites identified through TSIP. In these remediation efforts, extensive site mapping is undertaken to characterize the spatial distribution of contaminants, consultations are held with local area residents to help design the most effective and appropriate interventions, and biological samples of residents are taken, as appropriate, before and after remediation.

From 2012 to 2014, PE and researchers from the Mount Sinai School of Medicine in New York City, used data collected as part of the TSIP to calculate the burden of disease resulting from exposures at contaminated sites. The effort focused on 3 countries in Southeast Asia: India, Indonesia, and the Philippines. Chatham-Stephens et al.[7] used sampling data from individual sites and existing demographic information to conduct an exposure assessment. Dose-response was calculated using USEPA reference doses and slope factors[8] for noncarcinogenic and carcinogenic chemicals, respectively. An estimated incidence of disease was thus determined for various age groups. Finally, deaths (years of life lost [YLL]) were determined, and appropriate WHO disability weights (DW), discounting, and age weights were applied to calculate resulting years lost due to disability (YLD). YLD and YLL were summed at all sites and presented in the aggregate. The authors found that 828,722 disability adjusted life years (DALYs) resulted from contaminated sites in those 3 countries alone. A second paper[9] applied this same method to 3 additional countries in Latin America.

Sites Captured by TSIP. The TSIP method is not designed to survey all contaminated sites in a country. Rather sites are prioritized based on their perceived effect on human health. Moreover, finite resources limit the number of site visits. Relevant government agencies, academics, and others are interviewed to assist investigators to identify sites, although a systematic identification process similar to the National Priorities List of USEPA[10] is not in place. Underestimation of the number of sites and the attributable burden of disease therefore results.

To obtain data on the number of sites captured by TSIP relative to the total number of contaminated sites in a country and thus to assess the degree of underestimation, PE conducted a systematic census of hazardous waste sites in Ghana in 2014-2015.[11] Ghana was selected for this analysis because it is an LMIC with a heterogeneous industrial base and a highly urban population (51%).[12] Assessors targeted a randomly selected number of geographic quadrats for comprehensive assessment. The investigators physically walked all accessible streets in each quadrat to visually identify sites. Visual identification was supplemented by field-based sampling with portable x-ray fluorescence instruments to test soils for metals (InnovX Delta Series, Olympus, Bridgeport, CT, USA). The investigators identified 72 sites in the sampled quadrats. They then extrapolated these data to the country as a whole using 1 of 2 methods. The first method (regional), which used cluster random sampling, estimated the regional number of waste sites first and then summed them to find a total in Ghana within a particular confidence interval. The second method (countrywide) estimated the total number of sites in Ghana, then "allocated" them to each region.[11]

Based on this extrapolation, the investigators estimated there were between 812 and 3075 contaminated sites in Ghana. By comparison, TSIP had screened 215 sites in Ghana through 2014. It was therefore calculated that the percentage of sites captured by TSIP was between 7% and 26%. On a population basis, it was estimated from these data that in Ghana there are between 31 and 115 contaminated sites per 1 million population. Of the sites identified in Ghana, 37% presented lead as the key pollutant.[11]

Informal ULAB Processing. The principal global use of lead today is in manufacture of plates and components for lead-acid storage, lighting, and ignition (SLI) batteries, which accounts for 85% of global lead consumption.[13] The lead used in batteries is derived from 2 main sources: primary lead mining and smelting (ie, newly mined from lead containing ore) and secondary lead smelting from used SLI batteries and other sources. Formal industrial lead smelters (both secondary and primary) are necessarily subject to the regulatory regimes of their host countries. Although many continue to present significant occupational hazards,[14-17] formal smelters at a minimum tend to be located in industrially zoned areas and have in place some sort of emissions and discharge control infrastructure.

Informal industry by contrast is characterized by lack of adherence to regulation, including zoning and pollution controls.[18,19] Accordingly, a higher number of informal industrial sites are located within residential areas than their formal counterparts and pollute more per unit than their formal counterparts. The TSIP program has encountered significant difficulty in assessing these sites, as operators have tended to be uncooperative. Little systematic research other than TSIP investigations has been undertaken to identify and map ULAB sites globally. Informal ULAB processers tend to be much smaller in scale and more widely distributed than their formal counterparts and are prone to changes in location in response to regulatory efforts or other forces.[20] Consequently it is a challenging exercise to develop a truly accurate assessment of their location and number.

Disability Adjusted Life Years. DALYs are a standard metric for burden of disease calculations. DALYs are used, most significantly, by the WHO and the IHME in their respective periodic updates of the global burden of disease (GBD). DALYs are calculated for a range of health outcomes including infectious and chronic diseases; however, their use with regard to contaminated sites remains limited.[2,21,22]

Environmental lead exposure can result in a number of health outcomes including renal effects and cardiovascular disease (CVD) in adults, and neurologic effects in children.[23] In their most recent GBD report, IHME modeled lead exposures resulting from aerial deposition of leaded gasoline.[2] Due in part to a lack of information on hotspots globally, IHME did not endeavor to estimate DALYs resulting these exposures. Based on exposure to leaded gasoline deposition only, IHME calculated between 4,199,925 and 15,594,412 DALYs for 2015.[2]

For the purpose of their analysis, IHME developed a complex algorithm that uses a range of required covariates.[2] Importantly, the IHME algorithm relies on both blood and bone lead estimates. Lead is a calcium analog and can be absorbed by bone as a result of chronic exposure.[24] IHME uses bone lead estimates to model both CVD and resulting deaths in older age groups. BLLs are only used by the IHME algorithm for the purpose of computing DALYs resulting from pediatric exposure. WHO by contrast presents a series of publically available tools that are more amenable to determining the attributable risk of lead exposure at specific sites using blood lead levels (BLLs) only.[25]

We endeavored to calculate the prevalence and resulting burden of disease of informal ULAB processors in LMICs.

METHODS

In the absence of a comprehensive dataset on ULAB sites, we used relevant existing statistics to infer an estimate of the number of sites and resulting exposures. We calculated the annual amount of lead entering the secondary market in each country and subtracted the amount of lead known to be recycled formally. We assumed the difference between these 2 numbers was the total amount of lead recycled informally.

Geographic Scope. Our analysis was restricted to LMICs only, defined by the World Bank as those countries with an annual per capita gross national income below US $12,475 per year.[26] Countries were further excluded for any one of the following reasons: Data were unavailable or could not be reasonably estimated; active countrywide conflict (eg, Syria) where models were unlikely to apply; Balkan countries, which although within the income guidelines, are unlikely to have widespread informal ULAB processing due to their proximate location to richer European neighbors. The remaining number of countries covered by the analysis presented herein is 90.

Estimating the Tonnage of Lead Entering the Informal Sector. To calculate the amount of lead entering the secondary market, we summed the metric tons generated annually from 6 different sources: automobile starter batteries (cars, trucks, buses, and other automobiles); motorbike starter batteries; uninterrupted power supplies (UPS); other transport vehicles (eg, forklifts); electric bicycles; and other vehicles and applications, such as green energy storage. Data provided by the Organisation Internationale des Constructeurs d'Automobiles (OICA) was used to determine the number of cars and trucks (including buses and other large automobiles) in use.[27] The number of motorbikes in use was provided by the ministries of transport for several Southeast and South Asian countries, and estimated elsewhere. We used a widely quoted estimate of 200 million electric bicycles for China.[28] We assumed zero electric bicycles for all other countries.

We used a model developed by the International Lead Association (ILA) to determine the amount of lead generated annually by each type of vehicle. After accounting for the weight of other materials in each battery, the calculator assumes a weight of 8.4 kg of lead for car batteries, 15 kg of lead for truck batteries, and 4 kg for both bicycle and motorbike batteries. Batteries expire more quickly in warm climates.[29,30] As most countries covered by the analysis fit within this category a life span of 2 years is assumed. Because trucks typically have 2 batteries, they are expected to produce ≥1 ULAB annually.

The remaining metric tons from motorbikes as well as the contribution from other sources is estimated using their relative proportions of market share provided by the Industrial Technology Research Institute (ITRI).[31] Car and truck batteries, for which we were provided values by the OICA, were assumed to comprise 52% of the total lead tonnage used in batteries. The remaining 48% was distributed among the following 5 categories: motorbike starter batteries (6%); UPS (10%); other transport vehicles (eg, forklifts) (9%); electric bicycles (9%); and other vehicles and applications (14%).

The total amount of lead formally processed in secondary smelters in each country (provided by the US Geological Service)[32] was subtracted from the total amount generated. The difference between these 2 values was assumed to enter the informal sector. This approach to calculating informal lead production as described is generally consistent with those used elsewhere.[33,34] The statistical calculation was set out as:

$$\text{Total}\,\text{Pb}_i = 1/52 * \left[\frac{\text{Cars}_i * .0084}{2} + \frac{\text{Trucks}_i * .015}{1}\right]$$

$$\text{Total}\,\text{Pb}_i - \text{FormRcyl}_i = \text{InformRcyl}_i$$

where:

Cars_i is the number of cars in use in country i
Trucks_i is the number of cars in use in country i
TotalPb_i is the total lead in metric tons entering the secondary market in country i
FormRcyl_i is metric tons of lead processed in the formal sector i
InformRcyl_i is metric tons of lead processed in the informal sector i

Estimating the Number of Informal ULAB Sites. We used 2 separate methods for estimating the number of informal ULAB processing locations. In the first approach (method 1), we used the tonnage estimates from the model described previously and estimated yearly output of informal secondary smelters. This method is described in detail later. In the second approach (method 2), we used the Ghana extrapolation to determine the total number of informal ULAB sites on a population basis.[11] The Ghana effort found 31 to 112 contaminated sites for every 1 million residents in the country, with 37% of all sites being contaminated with lead from informal ULAB processors. Here we assumed (as a lower minimum estimate) 31 sites, and accordingly 11.47 informal ULAB sites, for every 1 million residents in a given country. We applied the weights described below to this initial number.

In the first approach (method 1), we assumed that 100% of lead not entering the formal sector is recycled at informal ULAB processing sites. We defined these as informal workshops typically located in residential areas where battery casings are ruptured, often manually. Plates are extracted and ingots are formed through rudimentary smelting techniques with little protective equipment or emissions controls. We modeled 3 sizes of informal processors (small, medium, and large) each with a set annual volume (100, 500, and 1000 metric tons, respectively). We divided the overall stream of lead into these 3 groups, assuming 50% flowing to small operators, 35% flowing to medium operators, and 15% flowing to large operators. In the absence of an existing body of research on the prevalence and throughput of informal sector operators, we based the above estimates on limited PE site assessment data and consultations with experts. This calculation provided us with an initial estimate of the total informal processing sites in a country:

$$\frac{\mathrm{InformRcyl_i} * .5}{100_{\mathrm{sm}}} + \frac{\mathrm{InformRcyl_i} * .35}{500_{\mathrm{sm}}} + \frac{\mathrm{InformRcyl_i} * .15}{1000_{\mathrm{lg}}} = \mathrm{IntTotalSites_i}$$

where:

$\mathrm{InformRcyl_i}$ is the metric tons of lead processed in the informal sector in country i
$\mathrm{IntTotalSites_i}$ is the initial estimate of the total number of informal lead processing sites in country i
sm is small processors
md is medium processors
lg is large processors

To account for the influence of other factors on the total number of sites, we further weighted our initial estimate by 4 values: per capita gross domestic product at purchasing power parity (GDP PPP); percent of the country living in urban areas; percent of the overall economy derived from the informal sector; and percent of the overall economy derived from mining, manufacturing and utilities (MMU).

The rationale for inclusion of these elements is as follows:

1. GDP PPP: In the context of LMICs, the relatively high price of lead affords a profit margin for recyclers even at low volumes. As the income of countries increases, this margin diminishes and larger volumes are required to sustain profit, limiting the feasibility of informal operation. We use values provided by the World Bank for 2013.[35]
2. Percent of the economy based in the informal sector: A higher rate of informality for the economy as a whole was taken to indicate a higher rate of informality in the recycling sector. We used values presented by Schneider et al on the size of each country's informal sector in 2006 and 2007.[36]
3. Percent of the population living in urban areas: People are more likely to come into contact with informal processing sites in urban areas than rural areas. We used urban percentage rates provided by the World Bank for 2013.[12]
4. Percent of the economy based in MMU This parameter, provided by the United Nations Statistics Division (UNSD),[37] was the best indicator that we could identify of the overall level of industrial activity in a country. There are linkages between the formal and informal economies in LMICs, with growth in former potentially associated with growth in the latter.[38] We assumed this was the case regarding ULABs and used MMU data provided by UNSD for 2013.

Of the 4 parameters, GDP PPP was the most heavily weighted (0.75). No other parameter was more closely associated with the presence of informal battery processing sites than income. In HICs, for instance, these sites are essentially nonexistent, whereas they proliferate in LMICs. Thus this parameter is inversely weighted to increased income. GDP PPP is followed by percent urban (0.1) and equal weightings for percent MMU and percent informal (0.075). The marginally higher weighting for percent urban is intended to reflect the relative importance of population density on increasing risk of exposure. Weights affect the result based on their relative difference from values taken for the country of Ghana. Given that Ghana is the only country for which we have a reasonable country estimate, we assumed that countries that are poorer, more urban, more reliant on industry, and had higher rates of informality are more likely to have informal battery processing sites. We assumed the opposite for countries that are richer, less urban, less industrial, and less informal. The equation is as follows:

$$\mathrm{IntTotalSites_i} * \left(\mathrm{GDPWt_i} + \mathrm{InfWt_i} + \mathrm{UrbWt_i} + \mathrm{MMUWt_i}\right) = \mathrm{TotalSites_i}$$

where:

$\mathrm{IntTotalSites_i}$ is the initial estimate of the total number of informal lead processing sites in country i
$\mathrm{TotalSites_i}$ is the final estimate of the total number of informal lead processing sites in country i
GDP $\mathrm{Wt_i}$ is the weighted value for income i
Inf $\mathrm{Wt_i}$ is the weighted value for informality i
Urb $\mathrm{Wt_i}$ is the weighted value for urbanization i
MMU $\mathrm{Wt_i}$ is the weighted value for industrialization i

Estimates were provided on a subregional level to account for limited transboundary movement of

ULABs. ULABs were categorized as hazardous waste under the Basel Convention and accordingly documentation should be kept of transboundary import and export transactions. An assessment of these records was outside of the scope of the present effort and would be unlikely to affect the most significant results. By way of example, about 5.1 million metric tons of lead are formally recycled globally each year.[32] The countries covered by this study account for more than 2.3 million tons, leaving the balance to be recycled in HICs. The United States is the second largest secondary processor of lead in the world after China, recycling 1.1 million tons annually, however, high car ownership rates preclude the United States as a reliant on an overseas stream of lead.[32] The situation is similar in other industrially developed countries with significant secondary lead smelting (eg, Canada, Germany, Spain, Japan, Italy), thus we excluded these countries as relying on an overseas supply of batteries.

Estimating Exposures at Informal ULAB Sites. ULAB sites present a heterogeneous set of conditions. To estimate population exposures to lead at these sites we developed a series of exposure scenarios, reflecting first the relative size of populations exposed and second the severity of exposure.

To capture number of exposed people we modeled operations of 3 different sizes: those where 200 people were exposed (small), those where 500 people were exposed (medium), and those where 2000 people were exposed (large). As previously noted, we assumed that small operations account for 50% of ULAB recyclers globally; that medium account for 35%, and that large account for 15% of all operations.

To capture the severity of exposure we divided the populations at each site into 3 exposure scenarios (low, medium, and high). Low represents soil concentrations of 850 mg/kg, medium represents concentrations of 2500 mg/kg, and high represents concentrations of 5000 mg/kg. All sites (small, medium, and large) were divided identically, with 50% of populations falling in the lower group (850 mg/kg), 35% falling in the medium exposure group (2500 mg/kg), and 15% falling in the high-exposure group (15%).

Exposure scenarios were based on the results of 28 assessments carried out by PE at informal ULAB sites in the following 12 countries: Argentina (n = 4), Bangladesh (n = 2), the Dominican Republic (n = 1), Ghana (n = 1), India (n = 4), Indonesia (n = 2), Kenya (n = 2), Peru (n = 3), the Philippines (n = 4), Senegal (n = 1), Uruguay (n = 5), and Vietnam (n = 1). Eight of these assessments were comprised of >20 target soil samples (range, 20-553 samples, analyzed with a handheld InnovX Delta Series x-ray fluorescence instrument) and were considered "detailed" assessments for our purposes. A second group, considered "limited," was comprised of 10 assessments with ≥6 composite samples each, and 10 assessments with ≥3 composite samples each. All assessments were divided into tertiles based on the relative severity of contamination. Tertiles were then averaged across all assessments equally resulting in values for the low, medium, and high exposure groups (810, 2626, and 6993 mg/kg, respectively). Detailed assessments revealed much higher values for all exposure groups (1536, 6465, and 16,257 mg/kg, respectively) when compared with limited assessments (509, 1150, and 2937 mg/kg, respectively). In an effort to remain conservative, we capped the soil concentrations for each group to the values given above (850, 2500, and 5000 mg/kg, respectively).

We used the spatial extent of contamination from detailed assessments only to guide the development of our estimates of exposed populations. We drew concentric circles with radii of 100 m, 200 m and 300 m from the center of each site to determine three site sizes (small, medium, large). We then applied NASA Socioeconomic Data and Applications Center gridded population density data[39] to the actual extent of each site to determine the number of exposed people. In one case (Vietnam) we deferred to PE population estimates from the detailed assessment. We averaged the sites in each group to determine the relative population sizes (251, 1053, 2029) and adjusted these to the slightly more conservative values of 200, 1000, and 2000 for small, medium and large sites, respectively. To determine the proportion of each population in each exposure scenario (lower, medium, high) we drew three equidistant concentric circles from the center of each site. We assumed increased severity with increased proximity. The resulting rings for each scenario made up 11%, 33% and 55% of each defined area. We adjusted these slightly to 15%, 35% and 50% to account for the diffuse nature of sources at a ULAB sites and assumed even population distribution across the whole area.

Calculating Blood Lead Levels. Humans can become exposed to lead in soil either directly or in dust form through ingestion, inhalation, and dermal contact, with direct ingestion being the most common dominant pathway. Most inhaled soil, for instance, is trapped and ingested before entering the lungs.[40] Efforts have been made in HICs to estimate the amount of soil children ingest daily,[41,42] although comparatively little work has been done in this area in the LMIC context. Those studies that do exist indicate daily intakes of perhaps 4 to 5 times those in the United States.[43,44] In addition to incidental ingestion, the deliberate ingestion of soil, or geophagia, remains a common practice in LMICs.[45]

We used 2 separate methods to calculate the BLLs of exposed groups. To calculate the BLL for children, we used the USEPA's Integrated Exposure Uptake Biokinetic Model for Lead in Children, Windows version (IEUBK).[46] We adjusted the default intake values for soil from 85 to 135 mg/day to 250 to 400 mg/day to account for regional differences in soil ingestion.[43,44] All values for all other pathways were adjusted to zero. To calculate BLLs for adults, we used the USEPA Adult Lead Methodology (ALM).[46] We adjusted default intake values for soil from 50 to 200 mg/day and allocated an exposure frequency of 365 days instead of the occupationally adjusted 219.

An increase proportional to that of children would have resulted in an intake value of 148 mg/day, however Harris and Harper (2004) estimate intakes of 400 mg/day for adults as well as children. We opted for a more conservative approach and arbitrarily selected 200 mg/day.

Both the IEUBK and the ALM rely on age-specific exposures. To estimate the proportion of an exposed population within a given age group, we used unpublished age distribution values provided by the IHME and used in their most recent GBD calculations.[2] Using this method, we calculated BLLs for each of 17 different age groups in each of our exposure scenarios (low, middle, high).

Calculating Attributable Disability Adjusted Life Years. To calculate the DALYs resulting from lead exposure at informal ULAB recycling sites we applied publicly available WHO methods to the exposure estimates above. We did so for both resulting CVD and intellectual disability. We further augmented these calculations with a separate calculation for YLD for pediatric IQ decrement, following Chatham-Stephens and not used by the WHO.[7]

DALYs from Cardiovascular Disease. We used the Microsoft Excel-based calculator developed by the WHO to determine the attributable fraction of the CVD burden from lead exposure.[25] We input the geometric mean BLL of all adult exposures at all sites (21.2 μg/dL) to determine the sex-disaggregated attributable fraction of ischemic, cerebrovascular, hypertensive, and other heart diseases. We then applied these values to the most recent WHO GBD report country estimates.[21] Because the WHO provides values at the country level, we first scaled their results to our numbers of the exposed populations at each site for both low- and high-exposure estimates. As a result, the CVD rate at ULAB sites is assumed to be the same as the national level. No effort was made to estimate any increase in the overall CVD rate at sites as a result of disproportionate lead exposure. We did not adjust for comorbidity.

DALYs From INTELLECTUAL Disability. To determine the number of DALYs attributable to intellectual disability from lead exposure, we used the WHO Microsoft Excel-based calculator. We input the geometric mean BLL for all children (ages 0-4) at all sites (31.15 μg/dL) and entered the appropriate regional adjustment. This calculation resulted in an incidence rate of 6.49 to 8.34 cases of attributable mild mental retardation (MMR) from pediatric exposure for every 1000 people, and prevalence of 32.45 to 41.72 cases per 1000 people. The calculation also resulted in an incidence rate of 32.45 to 41.72 cases per 1000 for prenatal exposure, depending on region. For prenatal exposure, incidence and prevalence were taken to be the same.

We then used 2 separate methods for the calculation of DALYs from intellectual disability. The first (incidence) was developed and used by the WHO for GBD calculations from 1990 to 2010. We calculated the number of childhood and prenatal exposures at each site by applying IHME population distributions and World Bank birth-rate estimates to exposed populations.[2,47] We assumed the same demographic profile at the site as at the country level. We then applied the population-adjusted incidence values above to those estimates to determine the number of cases. Finally, we adapted the DALY spreadsheet and calculation described in Prüss-Üstün et al[48] to facilitate the calculation of YLD for a large data set. We used the contemporaneous disability weight of 0.361 for MMR from pediatric lead exposure and did not disaggregate by sex. The equation as used (for a single disabling event) is as follows (adapted from Prüss-Üstün et al):

$$\mathrm{YLD} = \mathrm{DW}\left\{\frac{\mathrm{KCe}^{\mathrm{ra}}}{\mathrm{r}+\beta^{2}}\left[\mathrm{e}^{-(\mathrm{r}+\beta)(\mathrm{L}+\mathrm{a})}\left[-(\mathrm{r}+\beta)(\mathrm{L}+\mathrm{a})-1\right]-\mathrm{e}^{-(\mathrm{r}+\beta)\mathrm{a}}\left[-(\mathrm{r}+\beta)\mathrm{a}-1\right]\right]+\frac{1-\mathrm{K}}{\mathrm{r}}\left(1-\mathrm{e}^{\mathrm{rL}}\right)\right\}$$

where:

a = age of death (years)
r = discount rate (3%)
ß = age weighting constant (eg, ß = 0.04).
K = age-weighting modulation constant (eg, K = 1).
C = adjustment constant for age weights (eg, C = 0.1658).
L = duration of disability (years)
DW = disability weight

The second method for calculating DALYs (prevalence) was developed and used by the IHME for the 2010 GBD report and is now the standard approach of both the IHME and the WHO. This method does not account for future disease resulting from exposures and as such does not employ discounting or age weights for the calculation of YLD. Rather, YLD are calculated in a straightforward multiplicative fashion shown in the following equation (adapted from the WHO[49]):

$$\mathrm{YLD}_{\mathrm{i}} = \mathrm{DW}_{\mathrm{i}} \times \mathrm{p}_{\mathrm{i}}$$

where:

YLD = years lost due to disability
DW = disability
p = prevalence

We used the prevalence values from the aforementioned WHO spreadsheet for MMR and applied them to the entire exposed population. Because the MMR DW for pediatric lead exposure (0.361) is no longer used by the WHO, we utilized the closest analog, mild intellectual disability with a DW of 0.1270. We further applied the DWs for borderline (0.0034), moderate (0.2930), severe (0.3830), and profound (0.4440) intellectual disability to the prevalence of each sequela.[49] To calculate prevalence of the borderline, moderate, severe, and profound intellectual disability, we used relative distribution percentages provided by the WHO for LMICs and extrapolated from cases of MMR.[49] We summed all resulting YLDs to determine attributable DALYs. Neither the incidence nor the prevalence method resulted in a value for YLL. DALYs for intellectual disability were therefore the result of YLD equations only. We did not adjust for comorbidity.

DALYs From IQ Decrement Not Resulting in MMR. Following Chatham-Stephens et al, we applied an additional DW for IQ decrement not resulting in MMR. All children at all sites covered by this analysis were expected to suffer lifelong impairment from IQ decrement resulting from lead exposure. Using the WHO calculator referred to above, we estimated that the vast majority (863 per 1000 population) were expected to have a decrement of ≥3.5 IQ points. An additional 135 children

Table 1. Estimated Number of Informal ULAB Processing Sites and Exposed Populations by Utilized Subregion

Region	Number of Sites (Method 1)	Population Exposed (Method 1)	Number of Sites (Method 2)	Population Exposed (Method 2)
Central Africa	126	72,532	157	90,205
East Africa	161	92,486	2702	1,553,638
North Africa	498	286,503	857	492,667
Southern Africa	529	303,962	1578	907,299
West Africa	351	201,849	2780	1,598,733
East Asia and Indochina	2959	1,701,232	6736	3,873,174
Former Soviet Union	564	324,511	776	446,387
Caribbean	90	51,536	213	122,293
Central and North America	569	327,108	819	471,096
South America	1352	777,252	1495	859,806
Middle East	438	251,836	741	426,153
South Asia	1369	787,023	8538	4,909,218
Southeast Asia (excluding Indochina)	1594	916,633	1849	1,063,431
Total	10,599	6,094,463	29,241	16,814,100

ULAB, used lead-acid battery.

per 1000 were calculated to have a decrement of 1.95 to 3.25 IQ points. IQ decrement resulting from pediatric lead exposure has long been acknowledged to result in decreased lifetime earnings and other adverse lifelong effects.[50-52] Despite this linkage, no DW currently existed that captured this impairment. As an alternative, we applied the DW for anemia (0.024).

In the incidence approach, we calculated IQ decrement for all non-MMR fetuses and children (ages 0-4) for all years of life. We used the applicable WHO DALY calculation (incidence) with full age weighting. We did not disaggregate by sex. In the prevalence approach, we calculated IQ decrement for fetuses, children, and adolescents (ages 0-14). We assumed 100% prevalence for all groups for whom we had not already calculated intellectual disability. We excluded possible IQ decrement for adults because we assumed an age of 15 years for all ULAB sites.

Table 2. DALYs by Health Outcome at Informal ULAB Processing Sites (Incidence Method)

Sequela	Low	High
Mild mental retardation	49,009	160,070
Total cardiovascular diseases	35,017	191,208
Hypertensive	4125	21,683
Ischemic	12,381	65,285
Cerebrovascular	14,224	80,575
Other cardiovascular diseases	4287	23,665
IQ decrement (other)	463,448	1,261,198
Total DALYs	547,474	1,612,476

DALY, disability adjusted life year; ULAB, used lead-acid battery.

Table 3. DALYs by Health Outcome at Informal ULAB Processing Sites (Prevalence Method)

Sequela	Low	High
Total intellectual disability	65,883	182,149
Intellectual disability – borderline	602	1652
Intellectual disability – mild	27,569	75,700
Intellectual disability – moderate	23,482	64,485
Intellectual disability – severe	10,233	28,097
Intellectual disability – profound	4448	12,215
Total cardiovascular diseases	35,017	191,208
Hypertensive	4125	21,683
Ischemic	12,381	65,285
Cerebrovascular	14,224	80,575
Other cardiovascular diseases	4287	23,665
IQ decrement (other)	25,896	88,114
Total DALYs	127,248	461,470

DALY, disability adjusted life year; ULAB, used lead-acid battery.

RESULTS

We estimate that there are 10,599 to 29,241 informal ULAB processing sites where human health is at risk in the 90 countries that we reviewed. We further estimate that 6 to 16.8 million people are exposed to lead at these sites, resulting in exposures to 557,000 to 1.8 million children (ages 0-4). Summary results of the number of sites and exposed populations are presented in Table 1.

We calculated a geometric mean BLL for children at ULAB sites of 31.15 μg/dL (range: 19.5-55.8 μg/dL) and a geometric mean BLL for adults of 21.2 μg/dL (range: 9.7-49.5 μg/dL). We estimated that these combined exposures resulted in 127,248 to 1,612,476 DALYs in 2013. Table 2 presents the results of the incidence method. Table 3 presents the results of the prevalence method. Table 4 presents a summary of all major findings organized by WHO region.

DISCUSSION

The main findings of the present study are that there are between 10,599 and 29,241 informal ULAB processing sites where human health is at risk in the 90 countries we reviewed; that battery recycling operations at these sites result in exposures to between 6,094,463 and 16,814,100 million people; and that these exposures to lead resulted in 127,248 to 1,612,476 DALYs in 2013.

Because global data on lead exposure at ULAB sites have not previously been available, none of the findings from our analysis were included in previous analyses of the GBD. In their most recent estimate of the GBD, the IHME modeled lead exposures resulting from aerial deposition of leaded gasoline.[2] They used these estimates to determine that 4,199,925 and 15,594,412 DALYs resulted globally in 2015 from exposure to lead from gasoline.

In the 90 countries covered by the present analysis, IHME estimates that approximately 3,092,760 and 7,017,424 DALYs resulted in 2015 from exposure to lead from gasoline. When that estimated burden of disease is added to the findings from this analysis, we calculated that the total burden of disease resulting from lead exposure in these 90 countries amounts to 3.2 million to 8.6 million DALYs in 2013. This finding indicates that lead is one of the largest environmental contributors to the GBD.

Table 4. Informal ULAB Sites, Exposed Populations, and Attributable DALYs by WHO Region

Region	Number of Sites (Method 1)	Population Exposed (Method 1)	Number of Sites (Method 2)	Population Exposed (Method 2)	DALYs (Low)	DALYs (High)
Africa	1348	775,058	7152	4,112,339	17,570	627,017
Europe	564	324,511	776	446,387	9128	46,978
Southeast Asia	3615	2,078,530	9625	5,534,601	42,825	395,526
Americas	2010	1,155,897	2527	1,453,195	21,629	118,157
Western Pacific	2222	1,277,492	6489	3,731,000	25,497	234,906
Eastern Mediterranean	840	482,975	2672	1,536,578	10,600	189,891
Total	10,599	6,094,463	29,241	16,814,100	127,248	1,612,476

DALY, disability adjusted life year; ULAB, used lead-acid battery; WHO, World Health Organization.

Throughout the present analysis, we tried to err in the direction of conservatism and to base our analysis on low-bound estimates. We noted a series of limitations in our approach, some of which resulted from this tendency to down-weight the numbers. First, our estimated geometric mean BLLs for both children and adults (31.15 and 21.2 μg/dL, respectively) are well below the levels that we have encountered in our own experience at ULAB sites in LMICs and are also below the levels reported in previously published studies. Thus, our calculations with regard to BLLs and DALYs likely resulted in a significant underestimate of the full magnitude of the disease burden due to lead exposure at ULAB sites globally. Comparable studies in China, for example, have found population-wide BLLs >100 μg/dL[53,54] and studies from other countries regularly report BLLs >40 μg/dL.[55-57] Our low estimates may reflect our reliance on environmental exposure estimates and on the IEUBK and ALM algorithms that were designed for a US context. We have tried to correct for this limitation by adjusting upward for the higher levels of ingestion that have been reported in LMICs. An alternative approach might be to apply a calculation for BLLs based on a meta-analysis of relevant literature to exposed populations.

Another potential shortcoming in the present analysis is that the algorithms we developed to estimate the number of contaminated sites in each region relied on a relatively small number of parameters and on a series of assumptions. Possibly incorrect assumptions included our use of a 100% recycling rate for ULABs and our exclusion of transboundary movement (beyond the individual subregions). Other potential shortcomings include the fact that national statistics in LMICs are potentially inaccurate. However, absent an alternative, we relied wholly on these statistics in many cases and elsewhere we extrapolate from them to fill gaps. We used Dowling et al. as a guide for developing these estimates and hedge toward the more conservative option.[11] Future, more detailed assessment at ULAB sites globally will result in refinement and very likely in increases in the estimates that we presented here.

With regard to our DALY calculations, we followed WHO methods closely on the calculation of DALYs resulting from intellectual disability and CVD with the exception of failing to account for comorbidity. We acknowledge that this may have resulted in a slight overestimate for the attributable fraction of lead exposure to these sequelae. More significantly we provided an additional DW for lifetime IQ decrement resulting from pediatric exposure. The result of this calculation disproportionately contributes to the overall disease burden presented. Pediatric lead exposure and associated IQ decrement result in a lifetime of adverse consequences, including decreased earnings, poorer educational and health outcomes, and higher rates of societal violence.[50,52,58,59] The existing list of WHO DWs simply does not account for these outcomes and as such falls woefully short of documenting the disease burden suffered by leaded children. We disaggregated all DALYs by sequelae and provided detailed accounting for our calculations, thus enabling the reader to elect to include this additional weighting or not.

We calculated DALYs for intellectual disability using 2 separate approaches. The first, prevalence, resulted in a range of 127,248 to 461,470 DALYs, whereas the second, incidence, resulted in the higher values of 547,474 to 1,612,476 DALYs. The prevalence approach is the most common method currently used in DALY calculations. Accordingly, these values are immediately comparable with those developed elsewhere. The incidence approach was used by the WHO until 2013 and is potentially more sensitive to certain characteristics of ULAB sites. Among them, this approach tends to more heavily weight nonfatal disease in children compared with adults.[49] We assumed an age of 15 years for all sites in our analysis, indicating that the future disease burden will be more significant than current population-wide prevalence suggests. Given that the incidence approach accounts for future morbidity, this is reflected in the results, whereas it is absent from the prevalence approach. Others have observed that for similar reasons the incidence approach may be preferable in cost-effectiveness analysis of interventions.[60] The different DALY values presented here do not reflect an actual difference in the amount of disease resulting from informal ULAB sites. They are simply 2 ways of presenting the same data.

The approach that we took here to assessing lead exposure at ULAB sites could be modified and applied to assess the disease burden resulting from exposures to other poorly quantified toxic chemicals at contaminated sites globally. Among the more prominent contaminants in the TSIP database are hexavalent chromium, obsolete pesticides, mercury, and radionuclides. It is likely that if analyses were undertaken of the disease burden resulting from exposures to these pollutants, the GBD attributable to pollution would increase still further.

The contamination resulting from informal ULAB sites presents a unique set of challenges, including its persistence, prevalence, and severity. Lead is highly immobile in the environment and is unlikely to migrate on its own from surface to subsurface soils where exposures would be reduced.[61] Accordingly, without intervention, ULAB sites will pose a risk to populations well into the future. By way of example, the phase down of leaded gasoline in the United States began in 1975, resulting in significant reductions over the next 2 decades and a total ban in 1995.[62] Soil lead concentrations in US urban areas, however, have remained elevated, contributing to 256,704 DALYs in 2015.[2,62,63] The case is similar globally. Most HICs phased down leaded gasoline along the same timeline as the United States.[64] At present, leaded gasoline is only sold in 2 countries: Algeria, Iraq, and Yemen.[65] Despite the absence of an ongoing source of leaded gasoline emissions, 4,199,925 and 15,594,412 DALYs result globally from legacy depostion.[66] In the case of informal ULAB sites, contaminated soils similarly could not be expected to naturally attenuate. To mitigate these long-term exposures, sites will need to be identified and characterized and site-specific remediation plans developed and executed.

Informal ULAB sites are diffuse and common. Haryanto, for instance, documented 71 distinct smelting locations in the Jakarta metro area.[20] These sites are disparately located in nearly all major areas of the city.[20] Similar spatial diffusion has been identified in those countries where TSIP has been conducted. ULAB operations are of low capital intensity and require little skill. They are therefore somewhat amenable to relocation; requiring a different policy response than their formal counterparts. In some cases, informal operators have been aggregated into industrial clusters that are spatially segregated from residential areas.[56,57] Elsewhere, sites have been shuttered by authorities only to relocate. Much has been written on adapting regulatory frameworks to the informal sector.[67,68] There is a need to evaluate informal ULAB sites in the context of this literature and develop appropriate regulatory responses.

ULAB sites present a uniquely severe risk to area residents. Indeed, the predicted pediatric BLLs in the present study are extremely rare in HICs, and then only seen in adults in very high-exposure occupational settings.[69] Surface soil lead concentrations resulting from ULAB sites are at least an order of magnitude higher than the highest set of roadside levels in HICs.[55,62] At its peak, leaded gasoline in the United States resulted in a mean BLL of 14.6 μg/dL for the population as a whole and 13.6 μg/dL in children.[70,71] In the present study, we predicted geometric mean BLLs of 31.15 μg/dL in children and 21.2 μg/dL in adults living near ULAB sites. We further stated that these predictions are much lower than actual the BLLs found by researchers at sites in the field[53-57] and that our predictions are very likely underestimates.

CONCLUSIONS

We estimate that in 2013 informal ULAB processing sites put the health of 6,094,463 to 16,814,100 million people at risk and contributed to 127,248 to 1,612,476 DALYs in the 90 countries we evaluated. These estimates indicate that this industry is currently causing widespread lead poisoning in

LMICs. Informal ULAB sites pose a unique threat to area residents in their persistence, prevalence, and severity. There is an urgent need to identify, characterize, and mitigate exposures at existing sites. There also is a need to identify appropriate policy responses and practical and effective long-term management approaches to minimize the creation of new sites.

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