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# Social cost of mining-related lead (Pb) pollution in Kabwe, Zambia, and potential remediation measures

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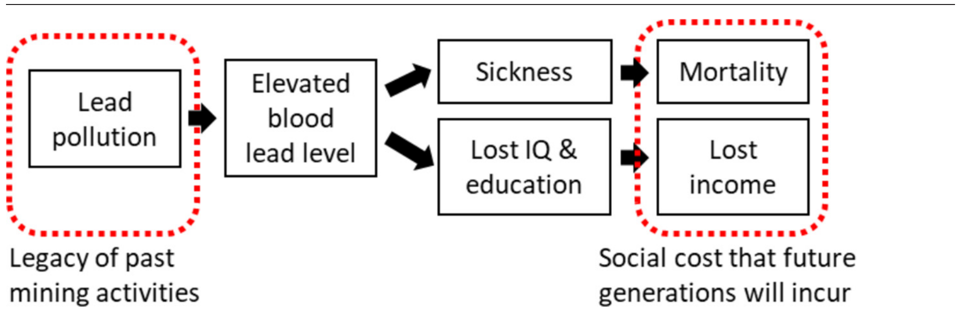
## HIGHLIGHTS

- We estimated the social cost of lead (Pb) pollution in Kabwe, Zambia.
- The income loss from IQ declines and the increased mortality were accounted for.
- We also examined the costs and benefits of potential remediation measures.
- Results: the social cost was significant, and remediation was socially profitable.
- An interdisciplinary approach between economics, engineering and toxicology.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Lead (Pb) pollution has been one of the major environmental problems of worldwide significance. It is a latent factor for several fatal illnesses, whereas the exposure to lead in early childhood causes a lifetime IQ loss. The social cost is the concept to aggregate various adverse effects in a single monetary unit, which is useful in describing the pollution problem and provides foundation for the design of interventions. However, the assessment of the social cost is scarce for developing countries. In this study, we focus on the lead pollution problem of a former mining town, Kabwe, Zambia, where mining wastes abandoned near residential areas has caused a critical pollution problem. We first investigated the social cost of lead pollution that future generations born in 2025–2049 would incur in their lifetime. As the channels of the social cost, we considered the lost income from the IQ loss and the lost lives from lead-related mortality. The results showed that the social cost would amount to 224–593 million USD (discounted to the present value). Our results can be considered conservative, lower bound estimates because we focused only on well-identified effects of lead, but the social cost was still substantial. Then we examined several engineering remediation measures. The results showed that the social cost can be reduced (the benefits of remediations) more than the costs of implementing remediation measures. This study is the first to investigate the social cost of mining-related lead pollution problem in developing countries. Our interdisciplinary approach utilises the micro-level economic, health and pollution data and integrates the techniques in economics, toxicology and engineering.

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## 1. Introduction

Lead (Pb) pollution is one of the major environmental problems of worldwide significance. Acute lead poisoning can be fatal, whereas a chronic exposure to lead can also be a latent factor for fatal illnesses and adversely affect the circulatory and nervous systems, cognitive abilities and development (Canfield et al., 2003; Centers for Disease Control and Prevention (CDC), 2012; Lanphear et al., 2005; Meyer et al., 2008). These health problems can further lead to socioeconomic problems such as poor learning abilities, productivity and income (Aizer et al., 2018; Miranda et al., 2007).

Social cost is a concept that signifies the adverse effects of an environmental problem imposed on a society or a group of people, which could include both market and non-market impacts. It aggregates the different types of effects and translates them into a single value in a monetary unit. Thus, the value of social cost describes the size and severity of a problem in a form comparable to other problems. Social cost also provides the foundation for the examination of potential interventions because its value is the lost welfare level that the society or individuals could enjoy if the problem did not exist.

In developed countries, the social costs and the benefits of remediation for various cases of lead pollution, including those caused by lead-containing products and past mining activities, have been examined (Gould, 2009; Guerriero et al., 2011; Landrigan et al., 2002; Pichery et al., 2011; Klemic et al., 2020). Consequently, developed countries have gradually tightened the standards for pollution and exposure levels. For example, the CDC of the USA lowered the reference blood lead level (BLL) from 60 μg/dL in the 1960s to 10 μg/dL in 1991, to 5 μg/dL in 2012, and to 3.5 μg/dL in 2021 (CDC, 2021). The use of lead in consumer products has been banned or reduced, and remediation has been conducted in former mining areas.

However, currently the worst cases of lead contamination are found in developing countries, often related to mining. In certain cases, the BLLs of residents are a few times or more higher than the standards in developed countries, and the health risks are concerning (Amankwaa et al., 2017; Bose-O'Reilly et al., 2018; Caravanos et al., 2014; Dooyema et al., 2012; Nakata et al., 2022; Yabe et al., 2015, 2020; Yamada et al., 2020). Despite the severity of the problems, the assessments of the social cost and the cost–benefit analyses of remediation are scarce. Ogunseitan and Smith (2007) and Attina and Trasande (2013) provide two such analyses, but they focused on the general population with low-level exposure to lead through the use of lead-containing products rather than on the critical and area-specific pollution cases, which engineering-based remediation measures are normally concerned with.

In this study, we evaluated the social costs of lead contamination and attempted a cost–benefit analysis of potential remediation measures, focusing on the lead pollution problem in Kabwe, Zambia. Kabwe is a former mining town, and the mining wastes have been abandoned in a dumpsite adjacent to residential areas. The town has been featured as one of the ten most polluted sites worldwide (Blacksmith Institute and Green Cross Switzerland, 2013) and the largest case of lead pollution in terms of persons affected (Toxic Site Identification Program; Yamada et al., 2020). The problem has received global attention, including international agencies and media,[1] and several research and remediation projects have been conducted (Bose-O'Reilly et al., 2018; Nakata et al., 2022). Nevertheless, lead pollution is still an ongoing problem in Kabwe.[2]

Specifically, we first estimated the social cost of lead pollution that individuals to be born in 2025–2049 would incur during their lifetime by comparing the status-quo case in which lead pollution levels remain the same as the current level and the hypothetical case in which lead pollution is eliminated. We focused on future generations, rather than the current residents, since the adverse effects of lead are often irreversible and future generations are the likely beneficiaries once remediation is implemented. Further generations to be born after 2050 were not accounted for, considering the difficulty in predicting socioeconomic and demographic conditions in the distant future. We considered two channels of the adverse effects, namely, the income loss due to the decreased IQ and education levels and the mortality from lead-related illnesses. These channels are often the main components of the social cost of lead pollution in other studies (Attina and Trasande, 2013; Gould, 2009; Guerriero et al., 2011; Klemic et al., 2020; Landrigan et al., 2002; Ogunseitan and Smith, 2007; Pichery et al., 2011). There could be several other channels of the social cost that may affect residents, such as the risk of non-fatal illnesses and crime related to the adverse effects on behaviour and emotional control (Aizer and Currie, 2019; Nevin, 2007); however, the quantification of these effects was not feasible in our context, and we focused on the abovementioned well-identified effects. In this sense, our framework offers conservative estimates that may represent the lower bounds of the actual social costs.

We then considered potential engineering remediation measures formulated by expert assessments and estimated the costs of implementing these measures and their benefits (that is, the reduction of the social cost of lead pollution). We hypothetically assumed that remediation would be initiated in 2025 and maintained through 2049 and accounted for the lifetime benefits for those born during this period. The remediation measures considered do not require advanced technologies and can be considered technologically feasible.

The contributions of this study are twofold. First, this study is one of the few to investigate the social cost of lead pollution in developing countries and is the first to assess mining-related pollution. Our assessment provides the basis for the policy designing to mitigate the lead pollution problem in Kabwe. It also sheds light on the scale and severity of the lead pollution problems in developing countries. The second contribution is methodological, and we integrated the techniques in engineering (the examination of the ambient lead level and remediation measures), toxicology (the examination of the BLL) and economics (the evaluation of the social cost) in a cross-disciplinary manner. Our framework is applicable to other cases of lead pollution, given that appropriate modifications are introduced.

The remainder of this paper proceeds as follows. In the remainder of this section, we describe the further background of lead pollution in Kabwe. In Section 2, we describe our framework and parametric settings to estimate the social cost of lead pollution and the costs and benefits of remediation measures. Section 3 demonstrates the results, and Section 4 discusses and concludes. Several technical details of our method and results are provided in the Supplementary Material.

### 1.1. Background on lead pollution in Kabwe

Kabwe, Zambia, is a town with a population of approximately 200,000 as of 2010. The town was founded around a lead and zinc mine in the early 1900s and continued to be one of the main mining sites of Zambia until the mine formally closed in 1994. Lead pollution owing to these mining activities has received attention since the 1970s (Clark, 1977), but the town is still highly polluted by lead. The primary cause of the sustaining pollution is the leaking of the mining waste abandoned in the dumpsite adjacent to residential areas (Fig. 1). The dumpsite has not been appropriately treated to prevent lead leakage, and lead-containing particles are easily transported to residential areas by wind during dry seasons and by waterflows during wet seasons.

The pollution levels of this area are extremely high. According to Kříbek et al. (2019), Doya et al. (2020) and our own data, the soil lead level (SLL) exceeds 500 mg/kg in residential areas surrounding the dumpsite, topping 10,000 mg/kg in the close neighbourhood of the dumpsite (Fig. 1) (for reference, the level of US regulation is 400 ppm, which is practically equivalent to mg/kg). Soil lead enters the human body through inhalation and

[1] For example, Human Rights Watch (August 23, 2019, https://www.hrw.org/report/2019/08/23/we-have-be-worried/impact-lead-contamination-childrens-rights-kabwe-zambia) and The Economist (December 10, 2020, https://www.economist.com/middle-east-and-africa/2020/12/10/how-a-lead-mine-in-zambia-has-blighted-a-town).

[2] The Zambian government has recently announced its intention to seek a long-term solution to the problem in 2022 (Human Rights Watch, June 22, 2022, https://www.hrw.org/news/2022/06/22/zambia-hope-kabwe-lead-poisoning-victims).

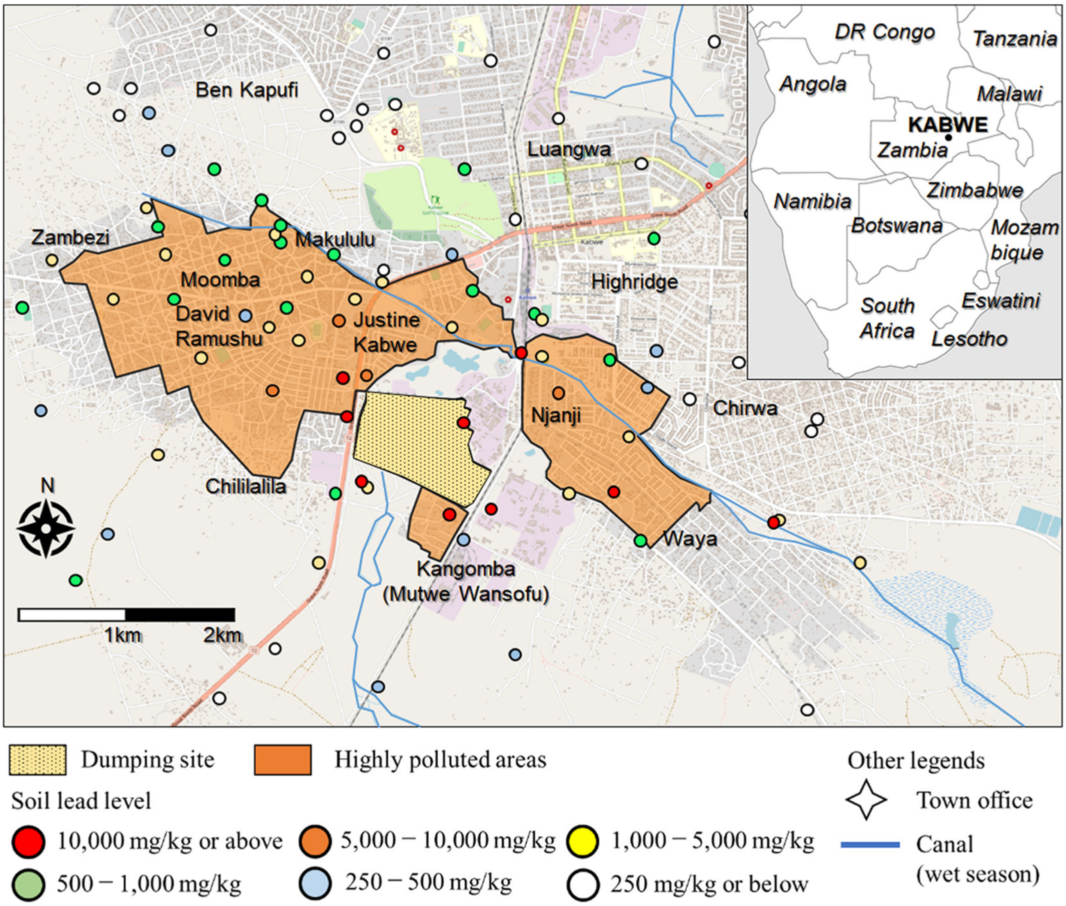


**Fig. 1.** Areas where remediation options are applied.
Note: The soil pollution levels are based on the data of our own, Doya et al. (2020) and Kříbek et al. (2019).

hand-to-mouth behaviours in young children. Further, home gardening of food items is common in Kabwe, even in highly polluted areas, and lead can also enter the human body when ingesting contaminated food.

Currently, lead pollution is estimated to affect 120,000–200,000 individuals in Kabwe (Toxic Site Identification Program; Yamada et al., 2020). Children's lead exposure is particularly concerning, with the BLLs of children in pollution hotspots exceeding 45 μg/dL, and even children not residing in the areas adjacent to the dumpsite experience BLLs >5 μg/dL. The BLL generally decreases as individuals become older owing to changing metabolism, behaviour and body mass, but the BLLs of adult residents are still a few times higher than international standards such as CDC (2021). Further, the adverse effects of lead are often irreversible, and lead exposure in childhood can have lifelong impacts (Lanphear et al., 2005; Meyer et al., 2008).

## 2. Methods

### *2.1. Framework to estimate social cost of lead pollution*

We estimate the total social cost of lead pollution that individuals born in 2025–2049 will incur in their lifetime. To calculate it, we compared the status quo case, denoted by $s = O$, in which the pollution level is kept the same as the current level and the hypothetical case, denoted by $s = N$, in which the pollution is eliminated, with $s$ indicating the pollution scenario. We also consider potential remediation measures. The benefit of remediation is the reduction of the social cost, which we estimate by comparing $s = O$ with the remediation cases in which the pollution level is reduced by remediation (although we consider three cases of remediation, we collectively index these cases by $s = R$).

We divided the Kabwe population into groups by birth cohort, gender and ward (the local administrative unit), indexed by $h$, $j$ and $r$, respectively. A birth cohort covers five years, with $h = 0$ corresponding to 2025–29, $h = 1$ to 2030–34 and so on. The time period, $t$, similarly indicates a five-year period with $t = 0$ corresponding to 2025–29, $t = 1$ to 2030–34 and so on.

The welfare (utility) level of individuals of cohort $h$ and gender $j$ in area $r$ during period $t$ is represented by $V^s_{h,j,rt} \times POP^s_{h,j,r,t}$, where $V^s_{h,j,r,t}$ is the welfare per person and $POP^s_{h,j,r,t}$ the size of the population group. These terms vary by $s$ as the pollution level affects both the welfare level and mortality. The lifetime welfare of this population group discounted to the value at $t = 0$, $LV^s_{h,j,r}$, is represented as follows:

$$LV^s_{h,j,r} \equiv \sum_{t=h}^{T(h)} V^s_{h,j,r,t} POP^s_{h,j,r,t} (1+\rho)^{-t} \qquad (1)$$

where $\rho$ is the discount rate used to discount the monetary values in future periods. The summation starts with $t = h$, when cohort $h$ starts its life. $T(h)$ is the final period for cohort $h$, which we set as the years when they become 60–64 years old, since the life expectancy at birth is 64.2 years in Zambia as of 2020 (World Bank, 2022) and the inclusion or exclusion of those aged 65 years or above does not greatly affect the estimation of the social cost (we revisit this issue in Section 2.2.4).

The cost of lead pollution for this population group is then defined by the difference between the lifetime welfare levels under $s = N$ and $O$, namely, $LV^N_{h,j,r} - LV^O_{h,j,r}$. The benefit of remediation is defined by the difference between $s = R$ and $O$, namely $LV^R_{h,j,r} - LV^O_{h,j,r}$. Thus, in both cases, our aim is to calculate $LV^s_{h,j,r} - LV^O_{h,j,r}$. By aggregating over all cohorts, genders


**Fig. 2.** Flow of estimation of social cost of lead pollution and benefit of remediation.

and wards, we obtain the social cost of lead pollution or the benefit of remediation for the entire Kabwe town as follows:

$$\sum_j \sum_r \sum_h \left(LV^s_{h,j,r} - LV^O_{h,j,r}\right) \quad (2)$$

These terms can be expressed more specifically (we suppress *j* and *r* for the remainder of this subsection). Let $Birth_h$ represent the number of births in cohort *h*, which we assumed would be unaffected by pollution and independent of *s*. Then denote the neonatal and non-neonatal mortality rates by $p^{s,neo}_h$ and $p^s_{h,t}$, respectively, which reflect both natural and pollution-related deaths. We assumed that births and neonatal deaths occur at the beginning of a period and that other deaths occur at the end of a period. Thus, $(1-p^{s,neo}_h)$ and $(1-p^{s,neo}_h)\prod_{\tau=h}^{t-1}(1-p^s_{h,\tau})$ represent the probability that an individual survives from birth to the beginning of period $t$. Assuming that there is no immigration of additional individuals to or emigration from this population group,[3] the population of cohort *h* after the neonatal period is $Birth_h(1-p^{s,neo}_h)$ and that in period $t > h$ is $Birth_h(1-p^{s,neo}_h)\prod_{\tau=h}^{t-1}(1-p^s_{h,\tau})$ .

The cost of pollution for cohort *h* is then expressed as follows:

$$\begin{aligned} LV^s_h - LV^O_h = Birth_h\Bigg[&\left(p^{O,neo}_h - p^{s,neo}_h\right)ELV^s_{h,h} \\ &+ \left(1-p^{O,neo}_h\right)\left(p^O_{h,h} - p^s_{h,h}\right)ELV^s_{h,h+1} \\ &+ \sum_{t=h+1}^{T(h)-1} ELV^s_{h,t+1}\left(p^O_{h,t} - p^s_{h,t}\right)\left(1-p^{O,neo}_h\right)\prod_{\tau=h}^{t-1}\left(1-p^O_{h,\tau}\right)\Bigg] \\ &+ Birth_h\Bigg[\left(V^s_{h,h} - V^O_{h,h}\right)\left(1-p^{O,neo}_h\right)(1+\rho)^{-h} \\ &+ \sum_{t=h+1}^{T(h)}\left(V^s_{h,t} - V^O_{h,t}\right)(1+\rho)^{-t}\left(1-p^{O,neo}_h\right)\prod_{\tau=h}^{t-1}\left(1-p^O_{h,\tau}\right)\Bigg] \end{aligned} \quad (3)$$

The equality follows the addition and subtraction of several terms. $ELV^s_{h,t}$ stands for the expected welfare that an individual acquires in the rest of life starting from period $t$, discounted to the value at $t = 0$, which is defined as follows:

$$ELV^s_{h,t} \equiv V^s_{h,t}(1+\rho)^{-t} + \sum_{\tau=t+1}^{T(h)} V^s_{h,\tau}(1+\rho)^{-\tau}\prod_{n=t}^{\tau-1}\left(1-p^s_{h,n}\right) \quad (4)$$

Eq. (3) explains the breakdown of social costs. The first bracket after the equality reflects the mortality cost. $(p^{O,neo}_h - p^{s,neo}_h)$ and $(p^O_{h,t} - p^s_{h,t})$ are the difference in the mortality rate during a given period. The value of a lost life is expressed by the welfare in the rest of life, $ELV^s_{h,t+1}$ or its variations. In the second bracket, $(V^s_{h,h} - V^O_{h,h})$ and $(V^s_{h,t} - V^O_{h,t})$ reflect the differences in the welfare levels in each period. These terms are multiplied by the survival probability in the status quo case, and the entire second bracket reflects the expected lifetime welfare loss of surviving individuals.

We quantified the value of the rest of life based on the value of statistical lives (VSL), which is a standard measure to assess the value of life and inclusive of both monetary consumption or income and non-market amenities. As for the lost welfare of surviving individuals, we accounted for the channel in which lead poisoning deteriorates the IQs and educational outcomes, and in which these deteriorations reduce their incomes. Fig. 2 illustrates the flow of these social cost channels.

Below, we describe the details of the methods, beginning with the estimation of the social cost of lead pollution.

### *2.2. Estimation of total social cost of lead pollution*

#### *2.2.1. Estimation of BLL*

We express the lead poisoning conditions of people with BLL. We reconstructed the distributions of the status quo BLLs in the study areas based on Yamada et al. (2020). Based on the BLL and socioeconomic data collected in 2017 through our original survey (Yabe et al., 2020; Yamada et al., 2020), we statistically (econometrically) estimated the following equation under the ordinary least squares:

$$\log BLL_i = \beta \log SLL_i + \boldsymbol{X}_i\boldsymbol{\gamma} + \varepsilon_i \quad (5)$$

where $i$ indexes individuals; $SLL_i$ is the SLL around the residence of $i$; $\boldsymbol{X}_i$ is the individual and household characteristics, such as age, gender, education level, household income and length of residence in Kabwe; and $\varepsilon_i$ is the error term. Although we demonstrated a single equation, we separately estimated the BLLs of children and adults. $\beta$ reflects the influence of the SLL on the BLL, including the inhalation and swallowing of lead-containing dust and the consumption of lead-containing food items grown in home gardens. We employ a logarithmic specification because their relationship is not necessarily linear (e.g., the efficiency of the lead absorption and excretion can change according to the intake level).

Then, we obtained the status quo BLL ($BLL^O_{h,j,r,t}$) by inputting the current SLL in each *r*, the corresponding values of age and gender, and the average individual and household characteristics in each *r* to the estimated equation. We used the estimated BLLs instead of the raw observed data because, firstly, the observed data were not available for all areas of Kabwe and, secondly, the use of the estimated BLLs allows us to overcome the self-selection bias arising from the voluntary nature of the BLL survey (Yamada et al., 2020).

For the case in which lead pollution is eliminated, we set $BLL^N_{h,j,r,t}$ at 2.5 μg/dL for all *h*, *j*, *r* and *t*. This level is below the latest CDC standard (CDC, 2021), and adverse effects of lead below this level have not been widely reported.

#### *2.2.2. Double-checking BLL–SLL relationship*

We double-checked the BLLs of the residents based on the integrated exposure uptake biokinetic model (IEUBK ver. 2) (US Environmental Protection Agency, 2022). The IEUBK model is a bottom-up method that predicts the BLLs of young children aged 0–6 years based on the ambient factors, such as the pollution levels of soil, air and food. In addition to the soil pollution data, we used our own food pollution data collected from 21 locations in Kabwe during 2020 and other pollution data calibrated from the existing studies (Nakata et al., 2016; Water Management Consultants Ltd, 2006). The strength of the IEUBK model is that it accounts for the ambient factors explicitly. However, a weakness is that several of its background parameters, such as dietary habits, behavioural patterns and housing conditions, are based on US data and may not fully reflect the conditions in Kabwe.

[3] Since people emigrating from Kabwe would still be affected by lead pollution, they are not necessarily excluded from the estimation. Conversely, people immigrating to Kabwe would not be affected by lead pollution as much as people having continuously exposed to lead since their birth, and the exclusion of these people from the calculation would not greatly affect the result. These points justify our assumption to ignore immigration and emigration.

As the IEUBK model does not estimate the BLLs of individuals aged seven years or above, we used the statistical estimation as the main method and the IEUBK model as a robustness check (see the Supplementary Material A for the details of the IEUBK model estimations).

*2.2.3. Population and mortality*

The mortality rates, $p^{s,neo}_{h,j,r}$ and $p^{s}_{h,j,r,t}$, are determined based on the United Nations (UN) projections on the national-level mortality rate for Zambia (UN Population Division, 2019), but we adjusted it by the urban–national disparity in Zambia based on the Central Statistical Office (CSO) of Zambia (2016), since Kabwe is an urban town, and by the relative risk ratio (RRR) of neonatal and non-neonatal lead-related mortality denoted by $RRR^{s,neo}_{h,j,r}$ and $RRR^{s}_{h,j,r,t}$, respectively. The number of births is determined by the population and crude birth rate (CBR). The CBR was extracted from the UN Population Division (2019), and we adjusted it by its urban–national disparity. We projected the population for 2025–2049 based on these mortality and fertility factors and the data of the latest census conducted in 2010 (CSO, 2012).

$RRR^{s}_{h,j,r,t}$ is a function of the BLL. To calculate it, we first listed up the causes of death, indexed by $k$, and, from the Global Burden of Disease (GBD) Study 2019 (GBD, 2020), we obtained the number of deaths from each cause in Zambia among each five-year age group and gender denoted by $\xi_{h,j,k,t}$—it does not specifically have the subscript for age, but $t-h$ specifies the age group. Then, we defined the RRR of cause $k$ under a given BLL, denoted by $\mu_k(BLL)$, which takes the value greater than one if a given BLL increases the mortality risk and takes the value of one otherwise. Then:

$$RRR^{s}_{h,j,r,t} = \frac{\Sigma_k \mu_k \left(BLL^{s}_{h,j,r,t}\right) \xi_{h,j,k,t}}{\Sigma_k \xi_{h,j,k,t}} \tag{6}$$

Among the causes of deaths, we regarded neoplasms, cardiovascular diseases, chronic obstructive pulmonary disease, and spontaneous abortion (referring to maternal deaths) as being dependent on BLL.

$RRR^{s,neo}_{h,j,r}$ is similarly defined, but we regarded preterm births and congenital birth defects as being related to lead pollution. Since these causes are related to maternal lead poisoning conditions, we assume that $\mu_k$ depends on the average BLL of women aged 20–39 years denoted by $MBLL^{s}_{r,t}$. Then:

$$RRR^{s,neo}_{h,j,r} = \frac{\Sigma_k \mu_k \left(MBLL^{s}_{r,t}\right) \xi_{a,j,k}}{\Sigma_k \xi_{a,j,k}} \tag{7}$$

$\mu_k$ was calculated based on the following studies (Borja-Aburto et al., 1999; Irgens et al., 1998; Jelliffe-Pawlowski et al., 2006; Lanphear et al., 2018; Lustberg and Silbergeld, 2002; McMichael et al., 1986; Schober et al., 2006; Steenland et al., 2017; Torres-Sánchez et al., 1999; Vinceti et al., 2001), as detailed in the Supplementary Material B.

*2.2.4. Quantification of mortality cost*

We measured the value of lost lives, $ELV^{s}_{h,t+1}$ or its variations in Eq. (3), using the VSL. The VSL is a standard measure of the value of life, but, since its value has not been specifically measured for Zambia, we followed the practice of the World Bank (Narain and Sall, 2016) and adjusted the VSL of the OECD average to the Zambian equivalent based on the GDP per capita. In addition, since the VSL increases as the economy grows, we also adjusted the VSL for future periods based on the GDP per capita growth rate in Zambia (see the Supplementary Material B for details).

A caution is that, whereas the VSL, or at least its material aspect, may seem to vary by age, the empirical studies have argued that the VSL does not have a clear relationship with age (Narain and Sall, 2016). A common practice in developed countries is to discount the VSL of the elderly aged 65 or above by a factor of 0.3–0.5 while keeping the VSL for the other ages constant. However, in case of Zambia, the life expectancy at birth was 64.2 years as of 2020 (World Bank, 2022), making the same discounting potentially unsuitable. Thus, we set the VSL of individuals aged 65 years or above to zero, which is also a reason for setting $T(h)$ at 60–64 years.[4]

*2.2.5. Quantification of IQ and income loss*

The income loss from the decreased IQ is formulated by $(BLL^{N}_{h,j,r,h} - BLL^{O}_{h,j,r,h})\sigma\theta_j y_{h,j,t}$. $BLL^{N}_{h,j,r,h} - BLL^{O}_{h,j,r,h}$ measures the difference in the BLL as of period $t = h$, when an individual is in ages 0–4 years. Because the exposure to lead in early childhood has a lifelong impact on IQ, we assumed that the BLL in these ages matters, rather than the BLL at given $t$. $\sigma$ is the IQ points lost per unit increase in the BLL. Based on Lanphear et al. (2005), we set $\sigma$ equal to 0.11, 0.19, 0.513 and 0 when the ages 0–4 BLL is >20, 10–20, 2.5–10 and < 2.5 μg/dL, respectively. $\theta_j$ is the income loss per unit point loss of the IQ. An IQ loss reduces the income both directly because of the loss of cognitive abilities that are useful in jobs and indirectly through the decreased education levels. The value of $\theta_j$ was determined based on studies on US workers (Salkever, 1995; Heckman et al., 2006), but we made an adjustment since income is more elastic to the human capital level in sub-Saharan countries than in developed countries (Montenegro and Patrinos, 2014). Summing up the direct and indirect effects, we set $\theta_j$ to be 2.10 % and 3.19 % for males and females, respectively (see the Supplementary Material B for more details of deriving these values). $y_{h,j,t}$ is the expected baseline income that accounts for unemployment, which varies by age group and gender. The income and unemployment rate were calculated based on our socioeconomic survey in Kabwe conducted in 2017 (Hiwatari et al., 2018), and we projected future incomes by assuming that the income level would grow at the same rate as the per capita GDP in Zambia. We assumed that individuals work from age 20 to 59, and $y_{h,j,t}$ for other age groups were set equal to zero.

*2.2.6. Other parameters*

When demonstrating the results, we express all monetary terms at the price level of 2017 and convert the local monetary terms to USD based on the average market exchange rate of 2015–2019 (World Bank, 2022). We discounted the monetary terms in future periods to the present value by setting $\rho$ =0.370, or 6.5 % per annum, following the discount rate for public project evaluation in low-income countries (Warusawitharana, 2014).[5] To project future per capita GDP growth rate, since the rate fluctuates substantially and is vulnerable to external shocks in Zambia (e.g., the average rate between 2001 and 2020 was 2.6 %, but it varied from −5.6 % to 7.1 % owing to resource booms, the global financial crisis, debt default and the COVID-19 pandemic; World Bank, 2022), we considered three cases of the growth rate: 1.5 %, 2.5 % and 3.5 % per annum, rather than setting a single parameter.

*2.3. Cost-benefit analysis of remediation measures*

*2.3.1. Remediation measures*

We examined the effects of engineering remediation measures and estimated the benefits (the reduction of the social cost of lead pollution) and the cost of implementing these measures. We assume that remediation is initiated in 2025 and maintained for 25 years until 2049. We estimated the lifetime benefits for individuals born during these 25 years.

The following remediation measures were chosen based on expert assessments and their technical feasibility for Kabwe. To prevent the primary source of lead, that is, leakage from the mining waste dumpsite, we considered a 1-cm cement mortar capping for the dumpsite. It prevents the lead

[4] We do not imply that the lives of old individuals do not have any value. Rather, our intention is to focus on the mortality for individuals having not yet reached the life expectancy since, if a person dies of a lead-related sickness before reaching the life expectancy, we could fairly clearly assume that the sickness shortened his/her life.

[5] Although we chose this level as a benchmark best fitting our study context, we recognize that there is no consensus value for this parameter applicable to all types of cost-benefit analysis (see for example, Moore et al., 2020).

leakage, and the SLL in all areas of Kabwe will gradually decrease through natural attenuation, although there is an uncertainty in the speed of the natural attenuation. Thus, we considered two cases: the fast-track case, in which the SLL halves every five years, and the slow-track case, in which the SLL halves every ten years (in other words, the SLL becomes approximately 70 % every five years).

As for residential areas that are particularly highly polluted ("highly polluted area" in Fig. 1), we additionally considered 10-cm soil removal and 30-cm soil replacement (excavation and removal of 30 cm of topsoil and its replacement with clean soil), depending on the pollution depth. The removed soil will be dumped in a new dumpsite covered with clean soil. Unlike the dumpsite remediation, these measures immediately lower the SLL. However, the excavation of the soil in certain areas may not be feasible owing to technical difficulties (e.g., the soil near existing structures) and opposition from the owners of land and buildings. Thus, we considered two cases regarding the coverage of these measures: one in which 75 % of the contaminated soil can be removed or replaced and the other in which 95 % can be removed or replaced. This would result in the SLL dropping to either 25 % or 5 %, respectively, of the current level initially and then further decreasing gradually through natural attenuation.

Both the initial and maintenance costs of each measure were estimated. The initial costs include the material costs, rental fees of machinery, labour costs, fuel costs and indirect costs (e.g. administrative costs). Maintenance is needed to prevent leakage of lead owing to the degradation of the capping. Since the maintenance costs arise in future periods, we discount them by factoring $(1+\rho)^{-t}$. Further details are provided in the Supplementary Material C.

### 2.3.2. Benefits of remediation

The benefits of these remediation measures were estimated in the same manner as the total social cost of lead pollution, except that we compared the pollution level that would be realised when each remediation measure is implemented ($s = R$) to the status quo case ($s = O$). Thus, there is an additional step to estimate the BLLs that will be realised when a given remediation measure is implemented, denoted by $BLL^{R}_{h,j,r,t}$. For individuals aged 0–4 years ($t = h$), we estimated the $BLL^{R}_{h,j,r,h}$ by inputting the lowered SLL in each area and period in Eq. (5). For those aged 5–9 years or above, their BLLs can decrease from $BLL^{R}_{h,j,r,h}$ by an aging effect and the effect of the gradual decrease in the SLL over time. However, whereas we input the respective age in Eq. (5) to reflect an aging effect, we input the SLL as of the time when they were 0–4 years, rather than inputting the SLL at a given period, because lead exposure can have a long-term effect and whether a reduction of the SLL after being exposed to a higher SLL does reduce the BLL is not clear. Thus, to be conservative and avoid overestimation of the BLL reduction, we account for only the aging effect to estimate $BLL^{R}_{h,j,r,t}$ for those aged 5–9 years or above.

## 3. Results

### 3.1. Social cost of lead pollution

Table 1 summarises the social cost of lead pollution in Kabwe that individuals born between 2025 and 2049 will incur in their lifetime. The total social cost was estimated to be 224–593 million USD, depending on the future economic growth rate. The cost of the IQ and income loss accounted approximately 90 % of the total social cost. Nevertheless, the cost of the mortality of 22.8–51.3 million USD is not negligible, and the lost lives amounted to 1557 (0.67 % of total deaths). The cost per birth divided the total cost by the number of births for this generation of individuals, a concept basically equivalent to the cost per person, and its value was 930–2465 USD. This value is substantial for the standard of Kabwe, where the average annual household income was approximately 4000 USD as of 2017.

In Table 2, we divided the entire town into three: highly polluted areas, where we apply the residential area remediation in the later analysis; other urban areas, mostly within 5 km of the dumpsite; and distant suburban and farming areas. To simplify the demonstration, we refer only to the case in which the economic growth rate is 2.5 % in the text (other cases are demonstrated in Table 2). The social cost per birth was the highest in highly polluted areas, where the average BLL of the residents was 24.6 μg/dL and the average BLL among children aged 0–4 years was 40.6 μg/dL. The total social cost was higher in other urban areas than in highly polluted areas owing to the large population in the former, but the per capita cost was 40 % lower. Both the total and per capita social costs were the smallest in distant suburban and farming areas, although children's BLLs still exceeded the CDC (2021) standard.

### 3.2. Cost and benefits of potential remediation measures

Table 3 shows the costs and benefits of remediation. We report the mean benefits because we have six parametric combinations owing to the assumptions on the speed of the SLL reduction and the economic growth rate, but the minimum and maximum are also reported in Table 3.

In all cases considered, the mean benefits always exceeded the costs. The cost of the dumpsite remediation was 35.1 million USD, whereas the mean benefit was 80.2 million USD. The benefit exceeded the cost in all but the case in which both the SLL decline and economic growth are slow. By removing 75 % of the soil in highly polluted residential areas, the cost was increased to 74.2 million USD, and the mean benefit increased to 105 million USD. If 95 % of the soil is removable, the cost became 84.7 million USD, and the mean benefit increased to 134 million USD.

The dumpsite remediation had the highest cost–benefit ratio and can be considered the most cost-efficient. The marginal profitability of remediation in residential areas depended on the proportion of removable soil. If 75 % of soil was removable or replaceable, the additional benefit compared to the dumpsite remediation was 24.8 million USD, but the additional cost was 39.1 million USD. Meanwhile, if 95 % of soil was removable or replaceable, the additional benefit was 53.2 million USD, exceeding the additional cost of 49.6 million USD. Thus, the residential area remediation should be done intensively, rather than sparingly, from the perspective of efficiency. This reflects the increasing return

**Table 1**
Social cost of lead pollution in Kabwe.

| Economic growth rate | Total social cost [million USD] | Cost per birth [USD] | Breakdown by channel [million USD] | |
|---|---|---|---|---|
| | | | IQ & income loss | Mortality |
| 1.5 % annum | 224 | 930 | 201 | 22.8 |
| 2.5 % annum | 362 | 1503 | 329 | 32.8 |
| 3.5 % annum | 593 | 2465 | 542 | 51.3 |

The monetary terms are under the 2017 price. The social cost that individuals to be born in 2025–2049 will incur in their lifetime.

**Table 2**
Social cost (area breakdown).

| Area | Total social cost [million USD] | Cost per birth [USD] | BLL [μg/dL] | |
|---|---|---|---|---|
| | | | All population | Children (0–4 years) |
| Highly polluted areas | 135 [84.4–218] | 2509 [1574–4070] | 24.6 | 40.6 |
| Other urban areas (<5 km from the dumping site) | 157 [96.8–259] | 1566 [963–2580] | 11.2 | 18.1 |
| Distant suburban areas and farming areas (>5 km from the dumping site) | 70.1 [42.8–116] | 880 [536–1455] | 5.5 | 8.6 |

The monetary terms are under the 2017 price. The social cost that individuals to be born in 2025–2049 will incur in their lifetime. Highly polluted areas correspond to the area specified in Fig. 1. Estimates under the assumption of 2.5 % economic growth rate are displayed at the top, and those under the assumptions of 1.5 % and 3.5 % growth rates are shown in brackets.

**Table 3**
Cost and benefit of remediation.

| Cost of remediation | | | Benefit of remediation | | |
|---|---|---|---|---|---|
| Total | Dumpsite | Residential area | Total benefit | IQ improvement | Mortality reduction |
| Only dumpsite remediation | | | | | |
| 35.1 | 35.1 | N/A | 80.2 [29.1–164] | 73.7 [26.8–151] | 6.5 [2.3–13.4] |
| 75 % of residential soil is removable | | | | | |
| 74.2 | 35.1 | 39.1 | 105 [43.5–202] | 96.5 [40.0–185] | 8.8 [3.4–17.3] |
| 95 % of residential soil is removable | | | | | |
| 84.7 | 35.1 | 49.6 | 134 [58.8–247] | 122 [53.8–225] | 11.6 [4.9–21.5] |

The monetary terms are in million USD under the 2017 price. As for the benefit, the mean is reported at the top row, and the minimum and maximum are reported in brackets.

of the BLL improvement with respect to the SLL improvement, which we discuss in the next subsection.

### 3.3. BLL estimation

Fig. 3 shows the trajectories of the BLLs of children aged 0–4 years after remediation is implemented. The dumpsite remediation gradually lowered the BLLs of children in all areas. However, with this remediation only, the BLLs in highly polluted areas would remain high even after 25 years. The residential area remediation immediately lowered the BLLs in highly polluted areas, and, by removing or replacing 95 % of polluted soil, the BLLs in highly polluted areas decreased to those in other urban areas.

The figure also highlights the following two further points. First, whereas the dumpsite capping would lower the SLL by 93 % or 75 % in two decades, depending on the speed of natural attenuation, the resulting BLL did not decrease as much. Second, in the case in which the residential area remediation was also implemented, the trajectory differed substantially by the proportion of removed or replaced soil. These points reflect the concave relationship between the BLL and SLL. Our statistical method estimated $\beta$ of Eq. (5) to be 0.33, implying $BLL = SLL^{0.33}$ times positive factors. That is, the BLL steeply increases with the SLL, when the SLL is low, but slowly increases, when the SLL is high (similar results were obtained under the IEUBK model; see Supplementary Material A). Thus, the BLL does not decrease as much as the SLL does. The relationship also conversely implies that an SLL reduction has an increasing-return relationship with a BLL reduction. Thus, 75 %- and 95 %-reduction cases of the residential area remediation led to a substantial difference in the resulting BLLs and benefits.

## 4. Discussion and conclusion

We investigated the social cost of lead pollution and the benefits and costs of potential remediation measures, focusing on the lead pollution problem in Kabwe, Zambia. As the sources of the social cost, we considered the future income loss owing to the decreased IQ and educational outcomes and the mortality from lead poisoning-related illnesses. Regarding remediation measures, we considered the cement capping of the mining waste dumpsite and the soil removal and replacement in highly polluted residential areas.

As for the social costs, the results showed that the generations born in 2025–2049 would incur a cost of 224–593 million USD in their lifetime (930–2465 USD per person). These costs are substantial for a town with a population of 200,000 and the average annual household income of 4000 USD. Further analysis showed that while the residents in the pollution hotspots would incur the largest social cost per person, the cost in other areas was also substantial, since the residents outside the hotspot, particularly children, also have BLLs above a standard criterion such as the CDC (2021). Thus, remediation, treatment or other form of intervention needs to consider the entire town, not only the hotspots. The future income loss constituted approximately 90 % of the social cost. An IQ reduction occurs even at a low BLL, and thus the IQ loss incurs a cost for the residents in almost all areas of Kabwe. In contrast, the share of the mortality cost was not high. Although the BLLs of children in hotspots were >10 times higher than the CDC (2021) standard of 3.5 μg/dL, which led to a substantial IQ loss, these levels generally do not cause immediate deaths found in several acute cases, such as the outbreak in rural Zamfara, Nigeria, that killed 25 % of children in 2010 (Dooyema et al., 2012). Nevertheless, chronic exposure to lead is a latent factor for several causes of death, and the social cost of mortality was not negligible in our case.

Our estimate of the social cost is rather conservative, and there could be additional social costs not accounted for in this study owing to the lack of data or their intangible nature. First, the risk of non-fatal illnesses and disorders can be substantial, and the disutility among people, medical expenses and labour supply loss can be considered parts of the social cost—although there is no specific medical treatment for lead poisoning in Kabwe, and medical expenses could be of little significance. Second, lead poisoning causes delinquency and crime through its effects on behavioural and emotional control (Nevin, 2007; Aizer and Currie, 2019). Recent studies focusing on developed countries account for medical expenses and crime although their volumes tend to be small compared to the cost of future income losses (Landrigan et al., 2002; Gould, 2009; Guerriero et al., 2011; Pichery et al., 2011). For example, in the estimation by Gould (2009), the health care cost and the increased crime correspond to approximately 16 % and 1 %, respectively, of the cost of the future income loss. Refining the estimate of the social cost through investigating these additional

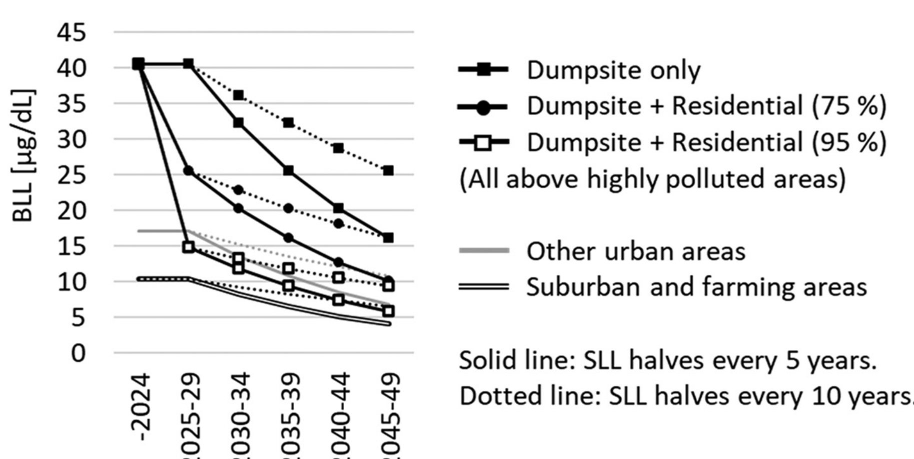


**Fig. 3.** Trajectories of BLLs under each remediation scenario.

channels would be a topic for further research. Nevertheless, our results provide a conservative, lower-bound estimate of the actual social cost.

As for remediation, we considered the cement capping of the dumpsite, which would gradually lower the SLL and provide benefits for all areas of Kabwe, and the soil removal and replacement in highly contaminated areas, which would immediately generate benefits for the residents in these areas. The results showed that the benefit exceeded the cost of implementing these engineering remediation measures. Thus, the first implication is that these remediation measures are worth their costs. The dumpsite capping has a particularly high benefit–cost ratio and is recommended since it prevents the main source of pollution.

The second implication is that, if implementing the residential area remediation, as long as it is feasible budget-wise, an implementation design to thoroughly remove polluted soil is recommended over that to a small-scale, sparing implementation that removes soil only from certain selected places. A sparing implementation for public spaces, such as main roads and school grounds, may seem efficient because a lot of residents may visit these places. However, a sparing implementation may not greatly reduce the BLL because the SLL reduction has an increasing return with respect to the BLL reduction. Furthermore, because young children before school ages in Kabwe, who are most sensitive to lead exposure, spend most of time around their houses, the soil removal in public spaces may not greatly prevent their exposure to lead.

However, these remediations alone would not immediately and perfectly eliminate pollution, and thus, a combination of these remediations with alternative interventions can be beneficial. For example, chelation therapy, which was conducted under the World Bank project of ZMERIP as a trial, may be provided until the SLL is sufficiently decreased. Another example is to promote the knowledge of lead and daily practices to avoid exposure to lead, such as not touching metal compound precipitated after the wet season, washing hands after touching soil, and not swimming in a canal and pond. In verbal communication during our surveys in 2017 and 2022, the general knowledge of lead pollution was limited. Interventions to improve the general awareness of lead pollution can thus help further reduce the social cost of lead pollution.

## CRediT authorship contribution statement

**Daichi Yamada:** Data curation, Formal analysis, Methodology, Writing – original draft. **Masato Hiwatari:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Daiju Narita:** Conceptualization, Writing – review & editing. **Peter Hangoma:** Data curation, Supervision, Writing – review & editing. **Bona Chitah:** Supervision, Writing – review & editing. **Hokuto Nakata:** Data curation, Formal analysis, Investigation, Project administration. **Shouta M.M. Nakayama:** Data curation, Investigation. **John Yabe:** Investigation, Project administration. **Mayumi Ito:** Data curation, Investigation, Methodology, Supervision. **Toshifumi Igarashi:** Data curation, Investigation, Methodology. **Mayumi Ishizuka:** Conceptualization, Funding acquisition, Supervision. **Golden Zyambo:** Conceptualization, Funding acquisition, Supervision.

## Data availability

The data that has been used is confidential.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data statement

The dataset used in the current study are not publicly available based on the ethical approval from the University of Zambia Research Ethics Committee, the Ministry of Health of Zambia and the Kabwe District Medical Office.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.161281.

## References

Aizer, A., Currie, J., 2019. Lead and juvenile delinquency: new evidence from linked birth, school and juvenile detention records. Rev. Econ. Stat. 101 (4), 575–587. https://doi.org/10.1162/rest_a_00814.
Aizer, A., Currie, J., Simon, P., Vivier, P., 2018. Do low levels of blood lead reduce children's future test scores? Am. Econ. J. Appl. Econ. 10 (1), 307–341. https://doi.org/10.1257/app.20160404.
Amankwaa, E.F., Tsikudo, K.A.A., Bowman, J.A., 2017. 'Away' is a place: the impact of electronic waste recycling on blood lead levels in Ghana. Sci. Total Environ. 601 (602), 1566–1574. https://doi.org/10.1016/j.scitotenv.2017.05.283.
Attina, T.M., Trasande, L., 2013. Economic costs of childhood lead exposure in low- and middle-income countries. Environ. Health Perspect. 121 (9), 1097–1102. https://doi.org/10.1289/ehp.1206424.
Blacksmith Institute and Green Cross Switzerland, 2013. The World's Worst 2013: Top Ten Toxic Threats. Pure Earth. (Accessed on August 29, 2022) https://www.worstpolluted.org/docs/TopTenThreats2013.pdf.
Borja-Aburto, V.H., Hertz-Picciotto, I., Rojas Lopez, M., Farias, P., Rios, C., Blanco, J., 1999. Blood lead levels measured prospectively and risk of spontaneous abortion. Am. J. Epidemiol. 150 (6), 590–597. https://doi.org/10.1093/oxfordjournals.aje.a010057.
Bose-O'Reilly, S., Yabe, J., Makumba, J., Schutzmeier, P., Ericson, B., Caravanos, J., 2018. Lead intoxicated children in Kabwe, Zambia. Environ. Res. 165, 420–424. https://doi.org/10.1016/j.envres.2017.10.024.
Canfield, R.L., Henderson, C.R., Cory-Slechta, D.A., Cox, C., Jusko, T.A., Lanphear, B.P., 2003. Intellectual impairment in children with blood lead concentrations below 10 μg per deciliter. N. Engl. J. Med. 348 (16), 1517–1526. https://doi.org/10.1056/NEJMoa022848.
Caravanos, J., Dowling, R., Téllez-Rojo, M.M., Cantoral, A., Kobrosly, R., Estrada, D., et al., 2014. Blood lead levels in Mexico and pediatric burden of disease implications. Ann. Glob.Health 80 (4), 269–277. https://doi.org/10.1016/j.aogh.2014.08.002.
Centers for Disease Control and Prevention (CDC), 2012. Low Level Lead Exposure Harms Children: A Renewed Call for Primary Prevention. (Accessed on August 29, 2022) https://stacks.cdc.gov/view/cdc/26445.
CDC, 2021. Blood Lead Reference Value. (Accessed on August 29, 2022) https://www.cdc.gov/nceh/lead/data/blood-lead-reference-value.htm.
Central Statistical Office (CSO) of Zambia, 2012. 2010 Census of Population and Housing. CSO, Lusaka, Zambia.
CSO, 2016. 2015 Living Conditions Monitoring Survey (LCMS) Report. CSO, Lusaka, Zambia.
Clark, A.R.L., 1977. Placental transfer of lead and its effects on the newborn. Postgrad. Med. J. 53 (625), 674–678. https://doi.org/10.1136/pgmj.53.625.674.
Dooyema, C.A., Neri, A., Lo, Y.-C., Durant, J., Dargan, P.I., Swarthout, T., et al., 2012. Outbreak of fatal childhood lead poisoning related to artisanal goldmining in Northwestern Nigeria, 2010. Environ. Health Perspect. 120 (4), 601–607. https://doi.org/10.1289/ehp.1103965.

Doya, R., Nakayama, S.M.M., Nakata, H., Toyomaki, H., Yabe, J., Muzandu, K., et al., 2020. Land use in habitats affects metal concentrations in wild lizards around a former lead mining site. Environ. Sci. Technol. 54 (22), 14474–14481. https://doi.org/10.1021/acs.est.0c00150.

Global Burden of Disease Collaborative Network, 2020. Global Burden of Disease Study 2019. Institute for Health Metrics and Evaluation, Seattle (Accessed on November 29, 2021) http://www.healthdata.org/gbd/2019.

Gould, E., 2009. Childhood Lead poisoning: conservative estimates of the social and economic benefits of lead hazard control. Environ. Health Perspect. 117 (7), 1162–1167. https://doi.org/10.1289/ehp.0800408.

Guerriero, C., Bianchi, F., Cairns, J., Cori, L., 2011. Policies to clean up toxic industrial contaminated sites of Gela and Priolo: a cost-benefit analysis. Environ. Health 10, 68. https://doi.org/10.1186/1476-069X-10-68.

Heckman, J.J., Stixrud, J., Urzua, S., 2006. The effects of cognitive and noncognitive abilities on labor market outcomes and social behavior. J. Labor Econ. 24 (3), 411–482. https://doi.org/10.1086/504455.

Hiwatari, M., Yamada, D., Hangoma, P., Narita, D., Mphuka, C., Chitah, B., 2018. Kabwe Household Socioeconomic Survey (KHSS) 2017 Report. (Accessed on August 29, 2022). http://satreps-kampai.vetmed.hokudai.ac.jp/images/publications/2018/The%20Kabwe%20Household%20Socioeconomic%20Survey%20(KHSS)%20Report%20(WEB).pdf.

Irgens, Å., Krüger, K., Skorve, A.H., Irgens, L.M., 1998. Reproductive outcome in offsprings of parents occupationally exposed to lead in Norway. Am. J. Ind. Med. 34 (5), 431–437. https://doi.org/10.1002/(sici)1097-0274(199811)34:5 < 431::aid-ajim3>3.0.co;2-t.

Jelliffe-Pawlowski, L.L., Miles, S.Q., Courtney, J.G., Materna, B., Charlton, V., 2006. Effect of magnitude and timing of maternal pregnancy blood lead (Pb) levels on birth outcomes. J. Perinatol. 26, 154–162. https://doi.org/10.1038/sj.jp.7211453 (2006).

Klemic, H., Mason, H., Sullivan, K., 2020. Superfund cleanups and children's lead exposure. J. Environ. Econ. Manag. 100, 102289. https://doi.org/10.1016/j.jeem.2019.102289.

Kříbek, B., Nyambe, I., Majer, V., Knésl, I., Mihaljevič, M., Ettler, V., et al., 2019. Soil contamination near the Kabwe Pb-Zn smelter in Zambia: environmental impacts and remediation measures proposal. J. Geochem. Explor. 197, 159–173. https://doi.org/10.1016/j.gexplo.2018.11.018.

Landrigan, P.J., Schechter, C.B., Lipton, J.M., Fahs, M.C., Schwartz, J., 2002. Environmental pollutants and disease in American children: estimates of morbidity, mortality, and costs for lead poisoning, asthma, cancer, and developmental disabilities. Environ. Health Perspect. 110 (7), 721–728. https://doi.org/10.1289/ehp.02110721.

Lanphear, B.P., Hornung, R., Khoury, J., Yolton, K., Baghurst, P., Bellinger, D.C., et al., 2005. Low-level environmental lead exposure and children's intellectual function: an international pooled analysis. Environ. Health Perspect. 113 (7), 894–899. https://doi.org/10.1289/ehp.7688.

Lanphear, B.P., Rauch, S., Auinger, P., Allen, R.W., Hornung, R.W., 2018. Low-level lead exposure and mortality in US adults: a population-based cohort study. Lancet Public Health 3, e177–e184. https://doi.org/10.1016/S2468-2667(18)30025-2.

Lustberg, M., Silbergeld, E., 2002. Blood lead levels and mortality. Arch. Intern. Med. 162 (21), 2443–2449. https://doi.org/10.1001/archinte.162.21.2443.

McMichael, A.J., Vimpani, G.V., Robertson, E.F., Baghurst, P.A., Clark, P.D., 1986. The Port Pirie cohort study: maternal blood lead level and pregnancy outcome. J. Epidemiol. Community Health 40 (1), 18–25. https://doi.org/10.1136/jech.40.1.18.

Meyer, P.A., Brown, M.J., Falk, H., 2008. Global approach to reducing lead exposure and poisoning. Mutat. Res. 659, 166–175. https://doi.org/10.1016/j.mrrev.2008.03.003.

Miranda, M.L., Kim, D., Overstreet Galeano, M.A., Paul, C.J., Hull, A.P., Morgan, S.P., 2007. The relationship between early childhood blood lead levels and performance on end-of-grade tests. Environ. Health Perspect. 115 (8), 1242–1247. https://doi.org/10.1289/ehp.9994.

Montenegro, C.E., Patrinos, H.A., 2014. Comparable Estimates of Returns to Schooling Around the World. World Bank Policy Research Working Paper 7020. (Accessed on August 29, 2022) https://openknowledge.worldbank.org/handle/10986/20340.

Moore, M.A., Boardman, A.E., Vining, A.R., 2020. Social discount rates for seventeen Latin American countries: theory and parameter estimation. Public Finan. Rev. 48 (1), 43–71. https://doi.org/10.1177/1091142119890369.

Nakata, H., Nakayama, S.M.M., Yabe, J., Lizambi, A., Mizukawa, H., Darwish, W.S., et al., 2016. Reliability of stable Pb isotopes to identify Pb sources and verifying biological fractionation of Pb isotopes in goats and chickens. Environ. Pollut. 208 (Part B), 395–403. https://doi.org/10.1016/j.envpol.2015.10.006.

Nakata, H., Nakayama, S.M.M., Yabe, J., Muzandu, K., Kataba, A., Ikeda-Araki, A., et al., 2022. Narrative review of lead poisoning in humans caused by industrial activities and measures compatible with sustainable industrial activities in Republic of Zambia. Sci. Total Environ. 850, 157833. https://doi.org/10.1016/j.scitotenv.2022.157833.

Narain, U., Sall, C., 2016. Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions. World Bank, Washington DC.

Nevin, R., 2007. Understanding international crime trends: the legacy of preschool lead exposure. Environ. Res. 104 (3), 315–336. https://doi.org/10.1016/j.envres.2007.02.008.

Ogunseitan, O.A., Smith, T.R., 2007. The cost of environmental lead (Pb) poisoning in Nigeria. Afr. J. Environ. Sci. Technol. 1 (2), 27–36. https://doi.org/10.5897/AJEST.9000111.

Pichery, C., Bellanger, M., Zmirou-Navier, D., Blorennec, P., Hartemann, P., Grandjean, P., 2011. Childhood lead exposure in France: benefit estimation and partial cost-benefit analysis of lead hazard control. Environ. Health 10, 44. https://doi.org/10.1186/1476-069X-10-44.

Salkever, D.S., 1995. Updated estimates of earnings benefits from reduced exposure of children to environmental lead. Environ. Res. 70 (1), 1–6. https://doi.org/10.1006/enrs.1995.1038.

Schober, S.E., Mirel, L.B., Graubard, B.I., Brody, D.J., Flegal, K.M., 2006. Blood lead levels and death from all causes, cardiovascular disease, and cancer: results from the NHANES III mortality study. Environ. Health Perspect. 114 (10), 1538–1541. https://doi.org/10.1289/ehp.9123.

Steenland, K., Barry, V., Anttila, A., Sallmén, M., McElvenny, D., Todd, A.C., Straif, K., 2017. A cohort mortality study of lead-exposed workers in the USA, Finland and the UK. Occup. Environ. Med. 74 (11), 785–791. https://doi.org/10.1136/oemed-2017-104311.

Torres-Sánchez, L.E., Berkowitz, G., López-Carrillo, L., Torres-Arreola, L., Ríos, C., López-Cervantes, M., 1999. Intrauterine lead exposure and preterm birth. Environ. Res. Sect.A 81, 297–301. https://doi.org/10.1006/enrs.1999.3984.

Toxic Sites Identification Program, .. https://www.contaminatedsites.org/ (Accessed on November 29, 2021).

United Nations Population Division, 2019. World Population Prospects 2019. (Accessed on November 29, 2021) https://www.un.org/development/desa/pd/news/world-population-prospects-2019-0.

US Environmental Protection Agency, 2022. Lead at Superfund Sites: Software and Users' Manuals. (Accessed on August 29, 2022) https://www.epa.gov/superfund/lead-superfund-sites-software-and-users-manuals.

Vinceti, M., Rovesti, S., Bergomi, M., Calzolari, E., Candela, S., Campagna, A., et al., 2001. Risk of birth defects in a population exposed to environmental lead pollution. Sci. Total Environ. 278 (1–3), 23–30. https://doi.org/10.1016/S0048-9697(00)00885-8.

Warusawitharana, M., 2014. The Social Discount Rate in Developing Countries. FEDS Notes. Board of Governors of the Federal Reserve System, Washington D.C. https://doi.org/10.17016/2380-7172.0029 (Accessed on August 29, 2022).

Water Management Consultants Ltd, 2006. Copperbelt Environment Project: Kabwe Scoping and Design Study Project Synthesis.

World Bank, 2022. World Development Indicators. (Accessed on August 29, 2022) https://datatopics.worldbank.org/world-development-indicators/.

Yabe, J., Nakayama, S.M.M., Ikenaka, Y., Yohannes, Y.B., Bortey-Sam, N., Oroszlany, B., et al., 2015. Lead poisoning in children from townships in the vicinity of a lead–zinc mine in Kabwe, Zambia. Chemosphere 119, 941–947. https://doi.org/10.1016/j.chemosphere.2014.09.028.

Yabe, J., Nakayama, S.M.M., Nakata, H., Toyomaki, H., Yohannes, Y.B., Muzandu, K., et al., 2020. Current trends of blood lead levels, distribution patterns and exposure variations among household members in Kabwe, Zambia. Chemosphere 243, 125412. https://doi.org/10.1016/j.chemosphere.2019.125412.

Yamada, D., Hiwatari, M., Hangoma, P., Narita, D., Mphuka, C., Chitah, B., et al., 2020. Assessing the population-wide exposure to lead pollution in Kabwe, Zambia: an econometric estimation based on survey data. Sci. Rep. 10, 15092. https://doi.org/10.1038/s41598-020-71998-5.