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Global burden of intellectual disability resulting from dietary exposure to lead, 2015

Clark Carrington[a], Brecht Devleesschauwer[b,c,*], Herman J. Gibb[d,e], P. Michael Bolger[f]

[a] Spoiled Hike LLC, Stanardsville, VA 22973, USA
[b] Department of Epidemiology and Public Health, Sciensano, Brussels, Belgium
[c] Department of Veterinary Public Health and Food Safety, Faculty of Veterinary Medicine, Ghent University, Merelbeke, Belgium
[d] Gibb Epidemiology Consulting LLC, 3033 Wilson Boulevard, Suite 700, Arlington, VA 22201, USA
[e] George Washington University Milken Institute School of Public Health, Washington, DC 20052, USA
[f] Exponent Inc., 1150 Connecticut Ave NW #1100, Washington, DC 20036, USA

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ABSTRACT

Lead is a ubiquitous dietary contaminant that occurs in food because of natural and anthropogenic sources and pathways of exposure. Lead adversely affects a number of tissues and organ systems and the severity of effect on each is dependent on the level and duration of exposure. The most sensitive and notable effects are those that occur on the nervous system. This is particularly the case in the exposure to the fetus, infant and child. Infants and children generally have higher lead exposures on a body weight basis. While lead exposure can come from many sources, a major source of exposure for at least some individuals comes from food.

Estimates for the impact of dietary lead on IQ were developed from published total diet studies. While most of these were designed to characterize intake of chemical contaminants on a national basis, some sampled market baskets from a single city. To develop global estimates, default ranges were created for countries with no data which encompassed the values encountered elsewhere. Blood lead levels and IQ decrements were estimated using functions previously developed by the WHO Joint Expert Committee for Food Additives. Since both the exposure and dose response components were variable and uncertain, a two dimensional Monte-Carlo simulation was used to develop the estimates for the impact of dietary lead on IQ. In addition to estimating blood lead and IQ decrements attributable to dietary lead from those countries with published market basket data, simulations were also run for WHO regions that sampled in the variability dimension based on the population size of the individual countries in each region.

Dietary exposure to lead occurs throughout the world. The global average IQ decrement attributable to dietary lead was 1.1. The total number of Disability-Adjusted Life Years (DALYs) arising from those IQ decrements were estimated to be 5.2 million DALYs, with an uncertainty range of 0–31 million DALYs. Significant uncertainties regarding exposure and dose-response relationships, however, warrant continued investigation.

1. Introduction

In 2006, the World Health Organization (WHO) launched an initiative to estimate the global burden of foodborne disease. In 2007, WHO established the Foodborne Disease Burden Epidemiology Reference Group (FERG), an advisory group of external experts, to implement this initiative. The FERG effort resulted in a publication on the global and regional estimates of the burden of foodborne disease (Havelaar et al., 2015). These estimates included the burden of disease from foodborne diarrheal disease agents, other bacteria and viruses, parasites, and three chemicals (aflatoxin, dioxin, and cyanide in cassava). As part of the FERG effort, Gibb et al. (2015) describe the foodborne burden of disease from these three chemicals in more detail and the regional burden from peanut allergen. The Chemical and Toxins

Abbreviations: AFR, African Region; AMR, Region of the Americas; DALY, Disability-adjusted life year; EFSA, European Food Safety Authority; EMR, Eastern Mediterranean Region; EUR, European Region; FAO, Food and Agriculture Organization of the United Nations; FERG, Foodborne Disease Burden Epidemiology Reference Group; GM, Geometric mean; GSD, Geometric standard deviation; IQ, Intelligence quotient; JECFA, Joint Expert Committee on Food Additives; SD, Standard deviation; SEAR, South-East Asia Region; YLD, Year Lived with Disability; WHO, World Health Organization; WPR, Western Pacific Region

* Correspondence to: Sciensano, Department of Epidemiology and Public Health, Rue J Wytsman 14, 1050 Brussels, Belgium.
E-mail addresses: brechtdv@gmail.com, brecht.devleesschauwer@sciensano.be (B. Devleesschauwer).

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Task Force of FERG focused its efforts on eight chemicals or toxins on which to make its estimates. These include the four aforementioned chemicals or toxins, which were described by Havelaar et al. (2015) and Gibb et al. (2015) and four metals or metal compounds – arsenic, lead, methyl mercury, and cadmium. The current paper is intended to help fill the gap of information on lead.

Lead is a metal with a long history of industrial use and human intoxication. Lead contamination of food arises mainly from incidental environment exposure or from food processing, handling and packaging. Environmental contamination may arise from many sources, including mining, burning coal, battery manufacturing, prior or current use of lead as a fungicide, and prior use of lead as a gasoline (petrol) additive. Lead will persist in soil and be transferred to crops long after the original environmental source is eliminated or curtailed. Atmospheric lead can also contaminate food through deposition on agricultural crops. Water used for irrigation or during processing is another potential source of lead contamination of food. Although lead exists in both organic and inorganic forms, only inorganic lead has been detected in food and is the lead species of public health concern.

The toxic effects of lead are generally observed only after a prolonged and continuous period of exposure (e.g., weeks to months and longer; World Health Organization, 2011). High-dose exposure is associated with clinically observable adverse effects on multiple organ systems. The most notable effects are on hematopoiesis, renal function and the central nervous system. The hematological effects often result in anemia, which is attributable to the inhibition of enzymes responsible for heme synthesis. Effects on the kidney include an acute renal nephropathy involving proximal tubule dysfunction and a more chronic nephropathy that is associated with atrophy of proximal and distal tubules. The neurological effects include encephalopathy characterized by brain edema and hemorrhage due to microvascular damage. All of these effects are potentially lethal.

Evidence of subclinical effects of lead in humans has come from epidemiological studies. Exposure to lead has been associated with increased mortality and a variety of cardiovascular and neurological effects in adults (World Health Organization, 2011). At low levels of exposure, lead is associated with learning deficits in children as measured by standardized intelligence tests (intelligence quotient (IQ); Lanphear et al., 2005). High lead exposures that result in clinically observable effects generally do not result from exposure via food consumption, and the exceptions involve unusual sources of contamination that occur locally. However, food may be an important contributor to lower level exposures to many people, especially children, throughout the world. Since a global view is more suited to considering low level exposures, this report will primarily focus on the impact of lead exposure from food on children's IQ.

The analysis described in this report has relied heavily on the recent assessment by the Joint Expert Committee on Food Additives (JECFA) of the WHO and the Food and Agriculture Organization of the United Nations (FAO). In particular, the assessment included a quantitative dose response assessment of lead and several key adverse health outcomes that have been documented in the epidemiological literature. Additional literature on dietary intake from studies conducted since the JECFA report were used as well.

There are three main difficulties with evaluating the global impact of dietary lead exposure on children's IQ. First, for many parts of the world, reliable consumption estimates and characterizations of lead concentrations in the food supply are unavailable. Second, lead is but one of many genetic, social, and environmental influences on behavior and intellectual performance. As a result, even though there have been many well designed epidemiological studies conducted over the last 30 years, there is substantial uncertainty associated with the quantitative relationship between lead exposure and IQ. Furthermore, the uncertainties are greatest at the lower levels of exposure encountered in many children. The third problem arises from the fact that the relationship between lead exposure and IQ is apparently nonlinear and that the diet can be but one of many sources/pathways (e.g., soil, dust, air) of lead exposure. As a result, the impact of dietary exposure to total lead exposure is dependent on the extent of other sources of lead exposure in each population considered and how much each contributes to total exposure.

2. Materials and methods

We followed a risk assessment approach to estimate the global impact of dietary lead exposure on children's IQ. In what follows, we describe the different elements of this approach in more detail – i.e., the dose-response relationship for lead and children's IQ, the exposure of children to lead from dietary sources, the integration of dose-response and exposure into estimates of incidence of intellectual disability, the translation of incidence estimates into Disability-Adjusted Life Years (DALYs), and finally, the simulation methodology used to propagate uncertainty and variability associated with the exposure distributions and dose-response models.

2.1. Dose-response relationship for lead and children's IQ

Many epidemiological studies designed to examine the relationship between exposure to lead and children's IQ have been conducted over the last 30 years. There have also been several meta-analyses conducted that have integrated results from multiple studies. JECFA (World Health Organization, 2000, 2011) developed dose-response relationships relating concurrent measurements of blood lead levels to children's IQ based on meta-analyses of key epidemiological studies. For this report, estimates were generated with the dose-response relationship documented by JECFA in 2011, which was based on a meta-analysis conducted by Lanphear et al. (2005). A bootstrap procedure was used to characterize the uncertainty in the dose response relationship arising from the uncertainty of the effect estimates in the meta-analysis.

The World Health Organization (2011) identified two preferred dose-response models. The Hill model provided the best fit of the estimates from the meta-analysis (Fig. 1). A bilinear model which has separate high and low dose slopes also fitted well (Fig. 2). The main difference between the two models occurred at doses below the range reported by epidemiology studies, with the Hill model generally yielding smaller IQ decrements than the bilinear model. With either model, the estimated impact as assessed by the slope of the dose-response relationship on IQ was greatest at levels of exposure below 15 μg/dL (Figs. 1 and 2). The Hill model produces the highest estimated IQ decrements at blood levels between 5 and 10 μg/dL (Fig. 1). Since neither model was entirely linear, the net effect of an incremental exposure from food is dependent on the magnitude of other exposures to lead. However, since the bilinear model has a constant slope at low levels of exposure, non-dietary exposures that may push overall lead exposure to higher levels impact the estimated dietary contribution to a lesser degree. Crump et al. (2013) also found that low dose effects on IQ from lead could be adequately modeled with a linear function. Therefore, the low level slope of 0.48 (0, 1.19) IQ points per μg/dL from the bilinear model was used to estimate dietary lead impacts in this analysis. Because the inflection point was one of the model uncertainties, there was no specific point that differentiated the two slopes.

Since these dose response models use blood lead concentrations as the dose metric, evaluation of dietary lead exposure requires quantification of the relationship between dietary lead exposure and blood lead concentrations. The present analysis used a linear slope with the range identified by World Health Organization (2000) of 0.05–0.16 μg/dL per μg/day of lead exposure. That analysis was based on the empirical relationship between blood lead in infants to the levels of lead in drinking water (Ryu et al., 1983). While this may overestimate blood lead concentrations in older children, the difference is slight since food intake relative to bone growth remains fairly constant through childhood (O'Flaherty et al., 1995).

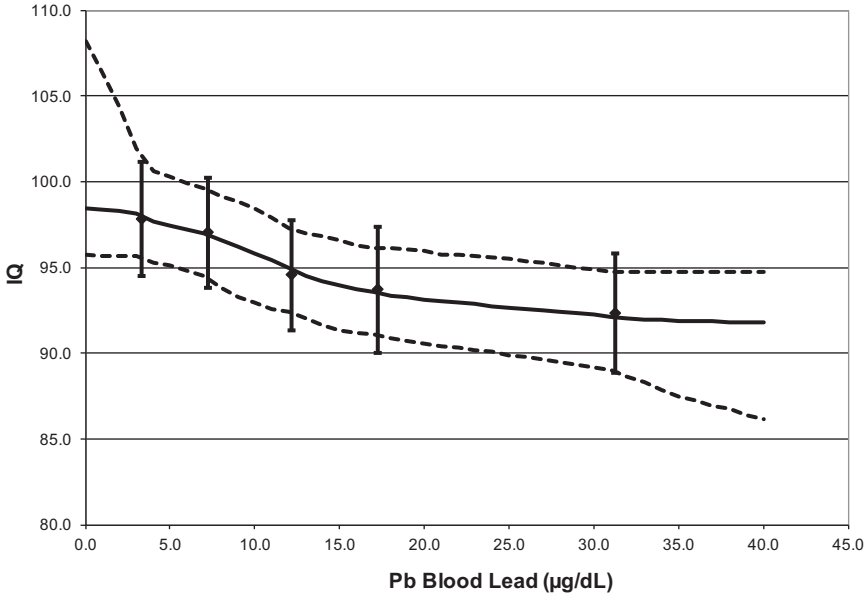

Fig. 1. Hill Model of Lanphear et al. (2005).

Since IQ loss is not considered to be a disease, case estimates of intellectual disability are used to generate disease burden estimates (Fewtrell et al., 2003). This involves calculating the increase in the number of children below 70 IQ points caused by the shift in the normal population distribution (i.e. with a mean IQ of 100 and a standard deviation [SD] of 15). Below 70 IQ is considered intellectual disability.

2.2. Exposure of children to lead from dietary sources

Lead may occur in many different foods, and total dietary exposure is a function of both the lead levels in different foods and the amount of each food consumed. Many countries have generated dietary lead exposure estimates as part of national total diet studies (World Health Organization, 2011). Where regional or country specific estimates were available, population distributions were developed from the individual reports. Because exposure distributions are generally skewed, population exposure estimates were characterized with lognormal distributions. However, the methodology used to develop the distributions varied with how the estimates were originally reported.

Lanphear et al. (2005) found concurrent lead exposure to have the strongest association with IQ decrements encountered with testing at seven years of age. However, since blood lead levels typically reflect many years of exposure and since there is no precise age at which lead impacts intellectual development, estimates corresponding to seven years of age and the preceding five years (i.e. ages 3–7) were used to characterize dietary intake of lead in children. Because the lead dose-response function use lead per person/day as the dose metric, dietary intake estimates that were originally reported on a body weight basis were converted to a per person basis, and a body weight corresponding to the median weight at five years of age, 18.25 kg, was used for the conversion (World Health Organization, 2006). However, it should be noted that the relationship between lead exposure and blood lead levels change relatively little throughout childhood; the fact that dietary intakes are higher during periods of high growth are counteracted by the

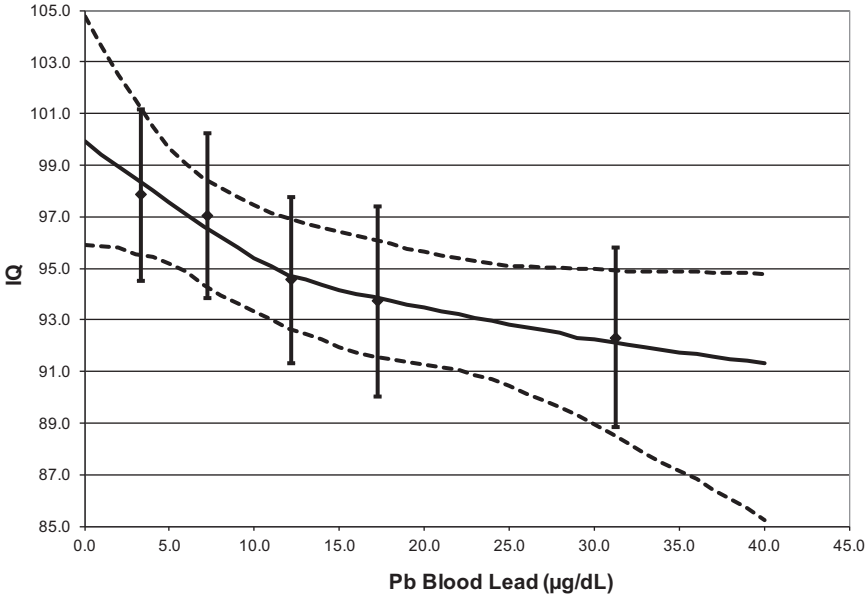

Fig. 2. Bilinear model of Lanphear et al. (2005).

fact that bone sequesters lead at the same time (O'Flaherty, 1995). As a result, when expressed on a per person basis, the age at which exposure is estimated is not a critical assumption.

2.2.1. Europe

A report issued by the European Food Safety Agency (EFSA) in 2012 developed estimates of dietary lead exposure for many individual countries and for the European Union as a whole. The EFSA estimates were expressed as arithmetic mean values and 95th percentiles, with central, upper, and lower bounds given for each. Using a triangular distribution to represent the uncertainty bounds, parametric bootstrapping was then used to generate a set of lognormal distributions that were consistent with the ranges provided in the European Food Safety Authority (2012) report. The analytic code for this step is available upon request. This distribution was used for other European and non-European countries where mean intake values were reported without characterization of a population range. A weighted average from the estimates for children was calculated from the estimates for toddlers (ages 1 or 2) and children (aged 3–10) with the average body weights used by EFSA (11.9 kg for toddlers and 23.1 kg for young children). Several European countries (Hungary, Ireland, and the United Kingdom) only reported lead intake values for either adults or the general population including adults and children. Children's intakes were estimated for these countries with an adjustment factor that ranged from 1.5 to 2; this range was based on the ratios encountered in countries where values from both children and adults were available from the European Food Safety Authority (2012) report. The geometric mean (GM) and geometric standard deviation (GSD) consistent with the arithmetic mean and standard deviation were calculated.

2.2.2. Australia

Lead intake estimates were developed from the total diet study reported in World Health Organization (2011) that had uncertainty ranges that treated samples below the level of quantitation as either zero or equal to the LOQ. While estimates were given from two studies, the more recent estimates from 2001 to 2002 were used in favor of the higher estimates from 1988 to 89 as they are a better indicator of current exposures. Per person intake values were used with Australian mean body weight values (reported in World Health Organization, 2011). Since intake values were reported for toddlers at age 2 and children at age 12, an age-weighted average for both the upper and lower bounds were used to estimate intake at age 5.

2.2.3. Cameroon

Lead intake estimates were developed from a total diet study funded by FAO in the capital city of Yaoundé (Gimou et al., 2014). Mean and 95th estimates for lead intake were reported for adults. In the absence of local data, we adopted the European adjustment factor, ranging from 1.5 to 2, to derive lead intake estimates for young children.

2.2.4. Canada

Health Canada (2011) conducted a series of eight total diet studies in major cities, with mean lead intakes reported for different age groups on a body weight basis. The estimate for children of ages 1–4 and 5–11 were used to calculate a weighted mean intake for each total diet study, and the average from all studies and the standard error of the mean was used to characterize the uncertainty of the mean value.

2.2.5. Chile

Lead intake estimates were developed from a total diet study conducted in Santiago by Muñoz et al. (2005) which yielded a per person mean intake value for adults. This was converted to a value for children with an adult body weight value of 68 kg and the standard assumptions cited previously for children's body weight and intake relative to adults.

2.2.6. China

Results from a total diet study conducted in 2000 were reported in World Health Organization (2011). Mean and 97.5th percentile intake values were reported on a per person basis for children aged 2–7. The GM and GSD consistent with those values were calculated.

2.2.7. Egypt, India, and Japan

Lead intake estimates for Egypt and India were developed from the values reported for adults in World Health Organization (2011). This was converted to a distribution for children with standard assumptions cited previously for children's body weight and intake relative to adults and a range of GSDs reported for European countries. Estimates for Japan were similarly developed with the range reported by Ohno et al. (2010).

2.2.8. Lebanon

Lead intake estimates were developed from the report by Nasreddine et al. (2006), which reported mean intakes as well as median, low and high end estimated intakes for adults on a per person basis. A lognormal distribution consistent with the percentile values was calculated and the GM and GSD were converted to values for children with the assumptions described previously for children's body weight and intake relative to adults.

2.2.9. New Zealand

Lead intake estimates were developed from the 2009 Total Diet report (New Zealand Ministry of Agriculture and Forestry, 2011), which reported mean weekly intakes on a per person basis, with a range that reflected uncertainty in samples below the level of quantitation. This was converted to a population distribution with a range of GSDs reported for other countries.

2.2.10. South Korea

Lead intake estimates were developed from the report by Koh et al. (2012). Population variability was characterized by fitting a lognormal distribution to the percentile estimate for the population.

2.2.11. United States

Lead intake estimates were developed from the mean and 90th percentile for 6-year-olds reported in World Health Organization (2011). After a body weight conversion for a 5-year-old (18.25 kg instead of 22 kg), per person intake values were calculated. Since these values were developed with the assumption that all analytical measures below the level of detection are zero, the nominal estimate was treated as the lower bound, and the upper bound was assigned a value of double the lower bound.

2.2.12. Global default

In order to develop global estimates, a default distribution was used for countries for which there were no data on dietary lead intake. The uncertainty ranges for this triangular distribution encompassed the ranges for all the countries for which there were available data, with a central value based on the average. While the average estimated exposure from the global default was similar to the European default, the uncertainty ranges were much broader.

2.3. Incidence of intellectual disability

As it is consistent with how measures of IQ are developed, it was assumed that IQ scores in each country have a mean of 100 and a standard deviation of 15. After the mean change in IQ attributable to lead in each country was calculated, the percentages of children in each country whose IQ scores would be shifted was determined, as a result of lead exposure, into the four categories of ID according to the International Classification of Diseases – i.e., mild ($50 < IQ < 70$), moderate ($35 < IQ < 50$), severe ($20 < IQ < 35$), and profound

(IQ < 20) (World Health Organization, 2017). Finally, the incidences of different levels of severity of lead-associated ID in a country were calculated using population data for the year 2015 from the United Nations World Population Prospects 2017 revision (https://esa.un.org/unpd/wpp/Download/Standard/Population).

2.4. Disability-Adjusted Life Years due to intellectual disability

Disability-Adjusted Life Years (DALYs) due to ID associated with childhood lead exposure were calculated according to the WHO Global Health Estimates methodology (World Health Organization, 2017). The case fatality rate of ID was assumed to be zero, therefore only Years Lived with Disability (YLDs) contributed to the DALYs. For each ID category, the YLDs are given by the product of the category-specific number of incident cases, duration, and disability weight. Total ID YLDs are obtained by summing the category-specific YLDs. As discussed in the exposure methodology section, the age-of-onset of lead-attributable ID was assumed to be five, and the resulting intellectual impairment was assumed to be life-long; the duration therefore corresponds to the life expectancy at the age of five. Life expectancies at the age of five by country were derived from the 2017 revision of the United Nations World Population Prospects (https://esa.un.org/unpd/wpp/Download/Standard/Population/). The disability weights for each ID category were adopted from the WHO Global Health Estimates study: 0.127 for mild ID, 0.293 for moderate ID, 0.383 for severe ID, and 0.444 for profound ID (World Health Organization, 2017).

While estimating the shift in the percentage of the population falling above and below predefined cutoff points is the methodology that has typically been used by WHO to estimate the health impact of environmental contaminants on intellectual disability, there are some shortcomings associated with it. First, even though the underlying rationale suggests otherwise, the practice misleadingly tends to ascribe the occurrence of some cases of severe ID entirely to the environmental contaminant. Second, because of the emphasis on the impact on the low end of the IQ population distribution, there is no consideration of the impact of the environmental contaminant on individuals who would not severely be impaired otherwise. As an alternative, approaches that monetize the value of an IQ point over the entire range have been employed (Grosse et al., 2002).

As an alternative, a DALY or QALY calculation could assign a value to incremental changes in IQ without attaching them to specific arbitrary thresholds. For example, the disability weights assigned by World Health Organization (2017) to decrements occurring below an IQ of 85 increase in a linear fashion, with a slope of about 0.0068 disability weight units per IQ point (Fig. 3). However, the value assigned to a borderline disability of 15 IQ points is assigned a value of 0.011 IQ points, or about 0.00073 disability weight units per IQ point. These bilinear slopes were used in the analysis as an alternative method to estimate disability weights across the full IQ distribution.

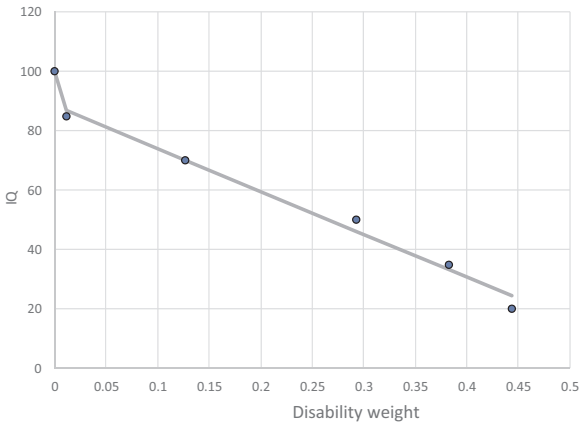

Fig. 3. IQ Decrements vs disability weights from World Health Organization (2017).

In line with the FERG estimates of the global burden of foodborne disease, DALY estimates were generated at country-level, and consequently aggregated into sub-regional, regional, and global estimates. The sub-regions are defined on the basis of the six official WHO regions, including the African Region (AFR), the Region of the Americas (AMR), the Eastern Mediterranean Region (EMR), the European Region (EUR), the South-East Asia Region (SEAR), and the Western Pacific Region (WPR). These regions are further subdivided into 14 sub-regions based on levels of child and adult mortality, denoted on a scale from A to E, with A having the lowest mortality rates and E the highest. The countries included in each of the 14 sub-regions are provided in Devleesschauwer et al. (2015).

2.5. Simulation methodology

Statistical estimates of the impact of dietary lead exposure on children's IQ were generated from the exposure distributions and dose-response models with the use of a two-dimensional Monte-Carlo simulation, where distributions representing population variability and uncertainty were sampled in separate dimensions, with 1000 iterations for variability and 300 or 1000 iterations for uncertainty. Since these numbers are not high enough to result in convergence at the upper percentiles, the same set of random numbers was used for the simulations for each country and region to make the estimates comparable. Given the large uncertainties inherent in the tails, the lack of convergence is not a significant issue since the uncertainties are quite large in any case.

Because the dose-response model does not have a representation of variability in response, the statistical variation exhibited in the estimates is entirely reflective of the variation of dietary exposure to lead. On the other hand, although there is uncertainty associated with some of the regional exposure estimates, the uncertainty distributions that produce the confidence intervals are largely reflective of the uncertainty in the dose response relationships between diet and blood lead levels and blood lead levels and IQ decrements.

Two dimensional simulations were also conducted for WHO regions and sub-regions. On the variability dimension, countries were assigned a frequency interval that was proportional to population size at an age of five. The European default distributions were used for countries in Europe without a country-specific estimate, while the global default distribution were used for all other countries without country-specific estimates. Uncertainty in both lead exposure and the dose-response relationship were represented in the same manner as individual countries.

3. Results

Estimated dietary lead intakes, blood lead increments, and IQ decrements are all listed by country in Tables 1–3. A few generalizations may be made about all three. First, in all cases, the lowest estimates were obtained for New Zealand, while the highest estimates were for Chile. Second, the quantified uncertainty ranges are not entirely comparable from country to country. Third, some reported estimates reflected sample error, while others did not. Finally, some estimates reflected uncertainty arising from samples below the level of detection, while others did not. In addition, while all the estimates are based on total diet studies, some of the studies are based on markets in single cities that may not reflect the rest of the country and also may not reflect intakes in rural areas.

3.1. Country-specific lead intake distributions

Median estimates for average dietary lead intake at age 5 at several population percentiles are listed in Table 1. Population average intakes

Table 1
Average and percentile (90% uncertainty interval) dietary lead intake estimates at age 5 (μg per person per day) by country.

Country	Average	10th percentile	Median	90th percentile	95th percentile	99th percentile
Australia	15.0 (14.9, 15.0)	6.3 (4.3, 8.9)	12.9 (11.4, 14.1)	26.4 (22.4, 30.1)	31.6 (25.2, 38.4)	43.9 (31.2, 59.8)
Belgium	27.3 (24.5, 30.0)	15.6 (13.8, 17.4)	25.4 (22.8, 28.0)	41.6 (37.7, 45.3)	47.0 (42.7, 51.1)	58.8 (53.7, 63.6)
Bulgaria	26.0 (22.9, 28.9)	16.3 (14.1, 18.4)	24.7 (21.7, 27.6)	37.4 (33.5, 41.3)	41.5 (37.3, 45.7)	50.2 (45.5, 54.9)
Cameroon	29.5 (26.3, 34.0)	4.4 (3.9, 5.1)	17.4 (15.4, 20.0)	68.4 (60.8, 78.7)	96.4 (85.8, 111.0)	180.4 (160.5, 207.7)
Canada	4.2 (3.5, 4.9)	1.8 (1.2, 2.5)	3.6 (2.9, 4.4)	7.4 (5.9, 9.0)	8.9 (6.8, 11.2)	12.4 (8.5, 17.3)
Chile	93.7 (83.6, 107.6)	39.6 (31.3, 49.4)	80.8 (78.5, 83.3)	165.5 (125.0, 216.9)	198.2 (140.4, 276.7)	275.1 (173.6, 431.1)
China	54.1 (54.1, 54.1)	13.7 (13.7, 13.7)	39.3 (39.3, 39.3)	113.3 (113.3, 113.3)	147.7 (147.7, 147.7)	239.5 (239.5, 239.5)
Czech Republic	26.7 (25.1, 27.6)	15.2 (14.8, 15.3)	24.9 (23.5, 25.5)	40.5 (37.6, 43.1)	45.8 (42.2, 49.2)	57.3 (52.3, 62.6)
Denmark	24.9 (22.5, 27.2)	16.4 (14.6, 18.1)	23.8 (21.6, 26.1)	34.8 (31.8, 37.6)	38.3 (35.1, 41.2)	45.5 (41.9, 48.8)
Egypt	23.3 (20.4, 26.3)	9.8 (6.7, 13.6)	19.9 (16.7, 23.5)	41.2 (33.9, 49.0)	49.5 (38.6, 61.6)	68.9 (47.6, 95.0)
Finland	26.9 (24.1, 29.5)	16.2 (14.4, 18.0)	25.3 (22.7, 27.9)	39.7 (35.9, 43.3)	44.5 (40.3, 48.4)	54.6 (49.7, 59.2)
France	21.2 (18.8, 23.4)	12.1 (10.3, 13.7)	19.7 (17.4, 21.9)	32.3 (29.4, 35.3)	36.6 (33.6, 39.8)	45.9 (42.7, 49.5)
Germany	17.2 (15.3, 19.2)	12.0 (10.4, 13.5)	16.7 (14.7, 18.6)	23.2 (20.8, 25.7)	25.2 (22.7, 27.9)	29.4 (26.6, 32.3)
Greece	17.0 (15.1, 18.8)	10.6 (9.5, 11.8)	16.1 (14.4, 17.9)	24.5 (21.9, 27.2)	27.3 (24.3, 30.2)	33.0 (29.4, 36.5)
Hungary	12.2 (10.4, 14.3)	7.4 (6.3, 8.8)	11.5 (9.8, 13.5)	17.9 (15.3, 21.0)	20.0 (17.1, 23.4)	24.5 (21.0, 28.5)
India	13.9 (12.1, 15.7)	5.8 (4.0, 8.1)	11.8 (9.9, 14.0)	24.5 (20.2, 29.1)	29.5 (23.0, 36.6)	40.9 (28.3, 56.5)
Ireland	15.9 (13.4, 18.9)	9.0 (7.7, 10.7)	14.8 (12.5, 17.6)	24.2 (20.3, 29.0)	27.4 (22.8, 32.9)	34.3 (28.4, 41.3)
Italy	21.0 (18.6, 23.3)	12.1 (10.4, 13.8)	19.6 (17.3, 21.9)	31.8 (28.6, 34.7)	36.0 (32.5, 39.0)	45.0 (41.0, 48.1)
Japan	20.1 (17.9, 23.0)	8.5 (6.7, 10.6)	17.3 (16.8, 17.8)	35.4 (26.7, 46.4)	42.4 (30.0, 59.2)	58.9 (37.2, 92.2)
Latvia	17.4 (15.8, 18.9)	8.8 (7.8, 9.8)	15.7 (14.2, 17.2)	28.3 (26.1, 30.3)	32.8 (30.4, 34.9)	42.9 (40.2, 45.2)
Lebanon	3.8 (3.2, 4.4)	2.4 (2.0, 2.8)	3.6 (3.1, 4.2)	5.4 (4.6, 6.4)	6.0 (5.1, 7.1)	7.3 (6.2, 8.5)
Netherlands	26.5 (24.1, 28.8)	16.3 (14.4, 18.0)	25.1 (22.6, 27.3)	38.7 (35.8, 41.6)	43.1 (40.1, 46.2)	52.6 (49.5, 56.1)
New Zealand	1.2 (0.1, 2.1)	0.5 (0.1, 1.0)	1.0 (0.1, 1.8)	2.0 (0.2, 3.7)	2.4 (0.3, 4.6)	3.2 (0.3, 6.7)
South Korea	4.8 (3.8, 5.8)	0.5 (0.4, 0.6)	2.4 (1.9, 2.9)	11.6 (9.3, 14.0)	17.3 (13.8, 20.9)	35.8 (28.6, 43.3)
Spain	20.7 (18.2, 23.1)	11.8 (10.4, 13.3)	19.3 (17.0, 21.6)	31.5 (27.9, 35.0)	35.7 (31.6, 39.5)	44.7 (39.6, 49.4)
Sweden	22.4 (20.2, 24.6)	13.8 (12.4, 15.3)	21.2 (19.1, 23.4)	32.6 (29.4, 35.7)	36.3 (32.7, 39.7)	44.2 (39.9, 48.2)
United Kingdom	15.2 (13.0, 17.8)	9.4 (8.1, 10.8)	14.4 (12.4, 16.8)	22.3 (18.9, 26.3)	24.9 (21.1, 29.4)	30.3 (25.7, 36.2)
United States	1.4 (1.0, 1.8)	0.3 (0.2, 0.4)	0.9 (0.6, 1.2)	3.1 (2.2, 4.0)	4.3 (3.0, 5.4)	7.4 (5.1, 9.4)
Europe default	**21.1 (18.8, 23.4)**	**14.3 (12.7, 15.9)**	**20.3 (18.1, 22.5)**	**29.0 (26.0, 32.1)**	**31.7 (28.4, 35.0)**	**37.3 (33.5, 41.2)**
Global default	**23.8 (5.0, 56.0)**	**9.9 (1.8, 24.7)**	**20.6 (4.1, 48.3)**	**41.0 (7.5, 100.5)**	**48.6 (8.9, 120.2)**	**66.5 (13.5, 173.1)**

ranged from 1.2 to 93.7 μg/day. At the 99th percentile, median estimates ranged from 3.2 to 275 μg/day. The median global default estimate, which reflects the range encountered in all other countries, was 23.8 μg/day for the population average, and 66.5 μg/day at the 99th percentile.

3.2. Country-specific blood lead increments

Median estimates for blood lead increments at several population percentiles, which are not expected to vary greatly with children's age, are listed in Table 2. Population average intakes ranged from 0.11 to

Table 2
Average and percentile (90% uncertainty interval) blood lead increments (Δμg/dL) attributable to dietary exposure by country.

Country	Average	10th percentile	Median	90th percentile	95th percentile	99th percentile
Australia	1.58 (0.83, 2.34)	0.64 (0.32, 1.14)	1.34 (0.71, 2.05)	2.75 (1.41, 4.33)	3.27 (1.64, 5.37)	4.42 (2.22, 7.96)
Belgium	2.90 (1.50, 4.35)	1.66 (0.85, 2.50)	2.71 (1.40, 4.06)	4.41 (2.30, 6.62)	4.98 (2.60, 7.48)	6.22 (3.25, 9.34)
Bulgaria	2.77 (1.41, 4.16)	1.75 (0.87, 2.63)	2.63 (1.34, 3.96)	3.99 (2.05, 5.98)	4.42 (2.29, 6.63)	5.34 (2.78, 8.01)
Cameroon	3.11 (1.59, 4.90)	0.47 (0.24, 0.74)	1.83 (0.93, 2.88)	7.22 (3.67, 11.35)	10.18 (5.18, 16.00)	19.04 (9.70, 29.95)
Canada	0.44 (0.23, 0.69)	0.18 (0.09, 0.32)	0.38 (0.19, 0.60)	0.76 (0.40, 1.22)	0.90 (0.47, 1.47)	1.24 (0.63, 2.21)
Chile	9.89 (5.04, 15.55)	4.12 (2.08, 6.69)	8.53 (4.41, 12.64)	16.65 (8.39, 29.90)	20.28 (10.00, 37.04)	28.39 (13.30, 56.28)
China	5.72 (2.99, 8.43)	1.45 (0.76, 2.14)	4.16 (2.17, 6.12)	11.98 (6.26, 17.64)	15.62 (8.16, 22.99)	25.34 (13.24, 37.30)
Czech Republic	2.81 (1.48, 4.16)	1.60 (0.83, 2.38)	2.61 (1.38, 3.89)	4.28 (2.25, 6.38)	4.84 (2.53, 7.26)	6.10 (3.16, 9.12)
Denmark	2.64 (1.37, 3.96)	1.74 (0.90, 2.62)	2.54 (1.32, 3.80)	3.68 (1.92, 5.53)	4.04 (2.11, 6.07)	4.80 (2.51, 7.20)
Egypt	2.48 (1.27, 3.72)	0.99 (0.49, 1.80)	2.12 (1.09, 3.28)	4.24 (2.21, 6.71)	4.99 (2.65, 8.14)	7.01 (3.58, 11.90)
Finland	2.86 (1.48, 4.29)	1.72 (0.88, 2.59)	2.70 (1.39, 4.04)	4.22 (2.19, 6.33)	4.72 (2.46, 7.08)	5.78 (3.02, 8.68)
France	2.25 (1.16, 3.39)	1.30 (0.64, 1.95)	2.10 (1.07, 3.16)	3.44 (1.79, 5.15)	3.88 (2.02, 5.82)	4.86 (2.55, 7.27)
Germany	1.84 (0.94, 2.77)	1.29 (0.64, 1.93)	1.78 (0.91, 2.68)	2.47 (1.28, 3.72)	2.69 (1.39, 4.04)	3.13 (1.62, 4.69)
Greece	1.81 (0.93, 2.72)	1.13 (0.58, 1.70)	1.72 (0.88, 2.58)	2.61 (1.34, 3.93)	2.90 (1.49, 4.36)	3.52 (1.81, 5.28)
Hungary	1.31 (0.66, 2.01)	0.80 (0.40, 1.23)	1.24 (0.62, 1.90)	1.92 (0.97, 2.94)	2.15 (1.08, 3.28)	2.62 (1.32, 4.01)
India	1.47 (0.75, 2.21)	0.59 (0.29, 1.07)	1.26 (0.65, 1.95)	2.52 (1.31, 3.99)	2.97 (1.58, 4.84)	4.17 (2.13, 7.07)
Ireland	1.71 (0.87, 2.63)	0.97 (0.49, 1.49)	1.59 (0.80, 2.45)	2.61 (1.31, 4.03)	2.95 (1.47, 4.57)	3.70 (1.83, 5.74)
Italy	2.23 (1.14, 3.36)	1.31 (0.65, 1.95)	2.09 (1.06, 3.14)	3.38 (1.75, 5.07)	3.81 (1.99, 5.72)	4.74 (2.48, 7.10)
Japan	2.12 (1.08, 3.33)	0.88 (0.45, 1.43)	1.83 (0.94, 2.71)	3.56 (1.79, 6.40)	4.34 (2.14, 7.93)	6.07 (2.85, 12.04)
Latvia	1.84 (0.96, 2.76)	0.94 (0.48, 1.41)	1.67 (0.87, 2.51)	2.99 (1.57, 4.47)	3.46 (1.82, 5.16)	4.53 (2.40, 6.71)
Lebanon	0.39 (0.21, 0.63)	0.25 (0.13, 0.39)	0.37 (0.20, 0.59)	0.57 (0.30, 0.90)	0.63 (0.33, 1.00)	0.76 (0.40, 1.21)
Netherlands	2.81 (1.46, 4.21)	1.73 (0.89, 2.60)	2.66 (1.38, 3.99)	4.09 (2.14, 6.13)	4.56 (2.40, 6.83)	5.58 (2.96, 8.29)
New Zealand	0.11 (0.01, 0.27)	0.04 (0.00, 0.12)	0.09 (0.01, 0.23)	0.18 (0.02, 0.48)	0.22 (0.02, 0.59)	0.30 (0.03, 0.87)
South Korea	0.50 (0.26, 0.79)	0.05 (0.03, 0.08)	0.25 (0.13, 0.39)	1.21 (0.63, 1.91)	1.80 (0.93, 2.85)	3.72 (1.93, 5.89)
Spain	2.20 (1.12, 3.32)	1.27 (0.64, 1.90)	2.06 (1.05, 3.10)	3.36 (1.72, 5.05)	3.80 (1.94, 5.71)	4.75 (2.44, 7.15)
Sweden	2.38 (1.23, 3.58)	1.47 (0.76, 2.21)	2.26 (1.17, 3.39)	3.46 (1.80, 5.20)	3.86 (2.00, 5.79)	4.69 (2.44, 7.04)
United Kingdom	1.63 (0.82, 2.50)	1.00 (0.50, 1.52)	1.54 (0.78, 2.36)	2.39 (1.20, 3.68)	2.67 (1.35, 4.11)	3.27 (1.65, 5.03)
United States	0.14 (0.07, 0.25)	0.03 (0.01, 0.05)	0.09 (0.04, 0.16)	0.32 (0.15, 0.55)	0.43 (0.20, 0.74)	0.74 (0.35, 1.29)
Europe default	**2.25 (1.15, 3.38)**	**1.52 (0.78, 2.29)**	**2.16 (1.11, 3.25)**	**3.09 (1.59, 4.64)**	**3.38 (1.74, 5.07)**	**3.98 (2.05, 5.97)**
Global default	**2.26 (0.39, 6.98)**	**0.91 (0.16, 3.09)**	**1.91 (0.33, 6.14)**	**3.92 (0.67, 11.67)**	**4.67 (0.79, 13.97)**	**6.43 (1.07, 19.69)**

Table 3
Average and percentile (90% uncertainty interval) estimated IQ decrements (ΔIQ) attributable to dietary lead exposure by country.

Country	Average	10th percentile	Median	90th percentile	95th percentile	99th percentile
Australia	0.72 (0.00, 2.16)	0.29 (0.00, 0.96)	0.61 (0.00, 1.92)	1.24 (0.00, 3.64)	1.51 (0.00, 4.43)	2.07 (0.00, 6.19)
Belgium	1.31 (0.00, 3.94)	0.75 (0.00, 2.24)	1.22 (0.00, 3.66)	2.00 (0.00, 6.02)	2.26 (0.00, 6.82)	2.84 (0.00, 8.55)
Bulgaria	1.25 (0.00, 3.71)	0.79 (0.00, 2.31)	1.19 (0.00, 3.52)	1.80 (0.00, 5.39)	2.00 (0.00, 5.99)	2.42 (0.00, 7.27)
Cameroon	1.41 (0.00, 4.07)	0.21 (0.00, 0.61)	0.83 (0.00, 2.40)	3.27 (0.00, 9.44)	4.61 (0.00, 13.31)	8.62 (0.00, 24.91)
Canada	0.20 (0.00, 0.60)	0.08 (0.00, 0.27)	0.17 (0.00, 0.52)	0.34 (0.00, 1.09)	0.41 (0.00, 1.32)	0.56 (0.00, 1.80)
Chile	4.48 (0.00, 12.95)	1.88 (0.00, 5.86)	3.91 (0.00, 11.44)	7.88 (0.00, 23.64)	9.25 (0.00, 28.09)	12.55 (0.00, 40.51)
China	2.61 (0.00, 7.79)	0.66 (0.00, 1.98)	1.89 (0.00, 5.66)	5.46 (0.00, 16.31)	7.12 (0.00, 21.27)	11.55 (0.00, 34.50)
Czech Republic	1.28 (0.00, 3.84)	0.73 (0.00, 2.16)	1.18 (0.00, 3.55)	1.96 (0.00, 5.93)	2.21 (0.00, 6.69)	2.77 (0.00, 8.32)
Denmark	1.20 (0.00, 3.60)	0.79 (0.00, 2.36)	1.15 (0.00, 3.45)	1.68 (0.00, 5.06)	1.85 (0.00, 5.57)	2.20 (0.00, 6.64)
Egypt	1.11 (0.00, 3.31)	0.45 (0.00, 1.52)	0.95 (0.00, 2.88)	1.90 (0.00, 6.03)	2.24 (0.00, 7.25)	3.12 (0.00, 9.92)
Finland	1.29 (0.00, 3.87)	0.78 (0.00, 2.32)	1.22 (0.00, 3.65)	1.91 (0.00, 5.75)	2.14 (0.00, 6.44)	2.63 (0.00, 7.93)
France	1.02 (0.00, 3.04)	0.58 (0.00, 1.70)	0.95 (0.00, 2.82)	1.56 (0.00, 4.69)	1.77 (0.00, 5.32)	2.22 (0.00, 6.71)
Germany	0.83 (0.00, 2.47)	0.58 (0.00, 1.70)	0.81 (0.00, 2.38)	1.12 (0.00, 3.34)	1.22 (0.00, 3.64)	1.42 (0.00, 4.24)
Greece	0.82 (0.00, 2.44)	0.51 (0.00, 1.53)	0.78 (0.00, 2.32)	1.18 (0.00, 3.52)	1.31 (0.00, 3.91)	1.59 (0.00, 4.74)
Hungary	0.58 (0.00, 1.76)	0.35 (0.00, 1.07)	0.55 (0.00, 1.66)	0.85 (0.00, 2.60)	0.95 (0.00, 2.91)	1.17 (0.00, 3.58)
India	0.66 (0.00, 1.97)	0.27 (0.00, 0.90)	0.57 (0.00, 1.71)	1.13 (0.00, 3.58)	1.33 (0.00, 4.31)	1.86 (0.00, 5.90)
Ireland	0.75 (0.00, 2.29)	0.43 (0.00, 1.32)	0.70 (0.00, 2.13)	1.14 (0.00, 3.50)	1.29 (0.00, 3.96)	1.62 (0.00, 4.96)
Italy	1.01 (0.00, 3.00)	0.58 (0.00, 1.71)	0.95 (0.00, 2.80)	1.53 (0.00, 4.60)	1.73 (0.00, 5.21)	2.16 (0.00, 6.53)
Japan	0.96 (0.00, 2.77)	0.40 (0.00, 1.25)	0.84 (0.00, 2.45)	1.69 (0.00, 5.06)	1.98 (0.00, 6.01)	2.69 (0.00, 8.67)
Latvia	0.84 (0.00, 2.52)	0.42 (0.00, 1.25)	0.76 (0.00, 2.27)	1.37 (0.00, 4.13)	1.59 (0.00, 4.80)	2.07 (0.00, 6.29)
Lebanon	0.17 (0.00, 0.56)	0.11 (0.00, 0.35)	0.17 (0.00, 0.53)	0.25 (0.00, 0.80)	0.28 (0.00, 0.89)	0.34 (0.00, 1.07)
Netherlands	1.28 (0.00, 3.84)	0.78 (0.00, 2.33)	1.21 (0.00, 3.62)	1.87 (0.00, 5.65)	2.09 (0.00, 6.32)	2.55 (0.00, 7.74)
New Zealand	0.04 (0.00, 0.22)	0.02 (0.00, 0.09)	0.03 (0.00, 0.19)	0.07 (0.00, 0.39)	0.09 (0.00, 0.46)	0.12 (0.00, 0.66)
South Korea	0.21 (0.00, 0.74)	0.02 (0.00, 0.08)	0.10 (0.00, 0.37)	0.51 (0.00, 1.79)	0.76 (0.00, 2.67)	1.57 (0.00, 5.53)
Spain	1.00 (0.00, 2.95)	0.57 (0.00, 1.68)	0.93 (0.00, 2.75)	1.52 (0.00, 4.51)	1.72 (0.00, 5.11)	2.15 (0.00, 6.40)
Sweden	1.08 (0.00, 3.23)	0.67 (0.00, 1.99)	1.02 (0.00, 3.06)	1.57 (0.00, 4.71)	1.75 (0.00, 5.25)	2.13 (0.00, 6.39)
United Kingdom	0.73 (0.00, 2.22)	0.45 (0.00, 1.35)	0.69 (0.00, 2.11)	1.06 (0.00, 3.21)	1.18 (0.00, 3.57)	1.43 (0.00, 4.37)
United States	0.06 (0.00, 0.23)	0.01 (0.00, 0.05)	0.04 (0.00, 0.15)	0.14 (0.00, 0.51)	0.19 (0.00, 0.70)	0.33 (0.00, 1.21)
Europe Default	**1.02 (0.00, 3.03)**	**0.69 (0.00, 2.04)**	**0.98 (0.00, 2.92)**	**1.40 (0.00, 4.17)**	**1.53 (0.00, 4.57)**	**1.80 (0.00, 5.38)**
Global Default	**0.93 (0.00, 5.08)**	**0.37 (0.00, 2.20)**	**0.74 (0.00, 4.44)**	**1.61 (0.00, 8.72)**	**1.92 (0.00, 10.76)**	**2.61 (0.00, 14.44)**

9.9 μg/dL. At the 99th percentile, median estimates ranged from 0.3 to 28.4 μg/dL. The median global default estimate, which reflects the range encountered in all other countries was 2.3 μg/dL for the population average, and 6.4 μg/dL at the 99th percentile.

3.3. Country-specific IQ decrements

For countries where dietary intake data were available, median estimates for IQ decrements attributable to dietary lead exposure at several population percentiles are listed in Table 3. Population average IQ decrements ranged from 0.04 to 4.48 points. At the 99th percentile, median estimates ranged from 0.12 to 12.55 points. The median global default estimate, which reflects the range encountered in all other countries was 0.93 points for the population average, and 2.61 points at the 99th percentile.

3.4. Country-specific intellectual disability estimates

For countries where dietary intake data were available, estimated changes in the percentage of individuals with mild, moderate, severe or profound ID attributable to dietary lead exposure are listed in Table 4. The median incremental change in the incidence of mild ID ranged from 1.4×10^{-4} (0.01%) to 2.1×10^{-2} (2.1%). The upper bound incremental change in the incidence of mild ID ranged from 7.8×10^{-4} (0.08%) to 9.9×10^{-2} (9.9%). The lower bound in all cases was zero. The estimated incremental changes in the incidence of moderate, severe and profound ID were all much lower.

3.5. Regional IQ decrements

Median estimates for IQ decrements attributable to dietary lead exposure at several population percentiles in WHO regions are listed in Table 5. In most cases, each regional estimate is dominated by one of the estimates listed in Table 3. Many of the regions have little or no country specific data and therefore largely correspond to the Global Default. The exceptions are those for AMR A, all three European sub-regions, SEAR B, and the two Western Pacific regions. AMR A is dominated by the estimates for the United States. Country-specific estimates are available for most of the population of EUR A. Because there is little country specific data for EUR B and EUR C, those estimates are dominated by the European default. SEAR B is dominated by the estimates for India, which in turn is based on a single market basket study constructed in Mumbai. Country specific data were available for the majority of the population in the Western Pacific. The estimates for WPR A reflect country-specific data from multiple countries, whereas WPR B is largely based on the estimates for China.

3.6. Disability-Adjusted Life Years

Estimated DALYs attributable to dietary lead exposure for each WHO region and sub-region are using DALY values from World Health Organization (2017) are listed in Table 6. These are tabulated both as rates per 100,000 persons and as total cases using age 5 as the time of onset.

Using the bilinear function derived in Fig. 3 yields nearly identical DALY estimates when an inflection point of 70 IQ points is used. For example, the global average IQ decrement of 1.10 IQ points results in 96 DALYs per 100,000. However, 82% of the DALYs come from the lower IQ slope that is applicable to the population majority with an IQ greater than 70. With an inflection point at 85 IQ, the DALYS per 100,000 increases to 187, with the 64% of the DALYs coming from the higher slope applicable to persons with an IQ of less than 85.

4. Discussion

The presence of lead in food, often at very low levels, is not an uncommon occurrence and the extent of its presence in food varies worldwide. Crops will take up lead from the soil they are grown in, at least some of which occurs naturally (World Health Organization, 2000). Concentrations at many locations throughout the world have

Table 4
Changes in intellectual disability incidence rates attributable to dietary lead exposure by country.

Country	Average ΔIQ		Median estimated incidence (per 100,000)				Upper bound incidence per (100,000)			
	Median	*UB*	*50 < IQ < 70*	*35 < IQ < 50*	*20 < IQ < 35*	*IQ < 20*	*50 < IQ < 70*	*35 < IQ < 50*	*20 < IQ < 35*	*IQ < 20*
Australia	0.72	2.16	264	8	0.177	0.001	869	28	0.659	0.006
Belgium	1.31	3.94	499	15	0.351	0.003	1778	62	1.595	0.015
Bulgaria	1.25	3.71	474	14	0.332	0.003	1649	57	1.447	0.013
Cameroon	1.41	4.07	540	17	0.383	0.003	1851	65	1.682	0.016
Canada	0.2	0.6	71	2	0.045	< 0.001	218	6	0.145	0.001
Chile	4.48	12.95	2092	75	1.981	0.019	9876	607	24.9	0.386
China	2.61	7.79	1081	35	0.854	0.008	4458	196	6.033	0.069
Czech Republic	1.28	3.84	487	15	0.341	0.003	1721	60	1.529	0.014
Denmark	1.2	3.6	454	14	0.316	0.003	1589	55	1.379	0.013
Egypt	1.11	3.31	417	13	0.288	0.002	1434	49	1.210	0.011
Finland	1.29	3.87	491	15	0.344	0.003	1738	61	1.549	0.015
France	1.02	3.04	381	11	0.262	0.002	1295	43	1.065	0.010
Germany	0.83	2.47	306	9	0.207	0.002	1014	33	0.791	0.007
Greece	0.82	2.44	302	9	0.204	0.002	1000	32	0.777	0.007
Hungary	0.58	1.76	211	6	0.139	0.001	690	22	0.505	0.004
India	0.66	1.97	241	7	0.160	0.001	783	25	0.583	0.005
Ireland	0.75	2.29	275	8	0.185	0.002	929	30	0.713	0.006
Italy	1.01	3	377	11	0.259	0.002	1275	42	1.044	0.009
Japan	0.96	2.77	357	11	0.244	0.002	1160	38	0.929	0.008
Latvia	0.84	2.52	310	9	0.210	0.002	1038	34	0.813	0.007
Lebanon	0.17	0.56	60	2	0.038	< 0.001	203	6	0.134	0.001
Netherlands	1.28	3.84	487	15	0.341	0.003	1721	60	1.529	0.014
New Zealand	0.04	0.22	14	0.4	0.009	< 0.001	78	2	0.050	< 0.001
South Korea	0.21	0.74	74	2	0.048	< 0.001	272	8	0.182	0.001
Spain	1	2.95	373	11	0.256	0.002	1249	42	1.018	0.009
Sweden	1.08	3.23	405	12	0.279	0.002	1393	47	1.166	0.011
United Kingdom	0.73	2.22	268	8	0.179	0.001	897	29	0.683	0.006
United States	0.06	0.23	21	1	0.013	< 0.001	82	2	0.052	< 0.001
Europe Default	**1.02**	**3.03**	381	11	0.262	0.002	1290	43	1.059	0.010
Global Default	**0.93**	**5.08**	346	10	0.235	0.002	2463	92	2.480	0.025

UB Upper Bound – 97.5th percentile.

been increased by anthropogenic uses of lead, particularly the past use of lead arsenate as a fungicide and tetraethyl lead as a gasoline additive. Although these uses have largely been discontinued, the lead that remains in the soil is difficult to avoid. Lead may also be introduced into food during processing or from packaging. Major reductions in lead in food in the United States has come about by eliminating the use of lead solder in food cans and tetraethyl lead in gasoline. One of the easiest sources of lead to avoid is that which is deliberately added. Although it is illegal in most places, lead chromate is nonetheless sometimes added to spices to hide economic adulteration (Gleason et al., 2014).

Despite the difficulties outlined in the introduction, some general conclusions may be drawn about the global impact of dietary exposure to lead. First, using the results from China and Europe as a general indicator, the impact of dietary lead on IQ is low but not entirely negligible, with average decrements of 1–2 IQ points, and decrements of 5 or more IQ points in children with higher dietary lead exposures. The estimated impacts in the U.S., Canada, and New Zealand are much lower. Although this is partly attributable to the fact that tap water was included in the Chinese estimates and the food categories used for different regions are not entirely identical, it is also clear that U.S. lead

Table 5
Average and percentile (95% uncertainty interval) estimated IQ decrements (ΔIQ) attributable to dietary lead exposure by World Health Organization region.

Region	Average	10th percentile	Median	90th percentile	95th percentile	99th percentile
Africa (AFR)	0.93 (0.00, 5.03)	0.37 (0.00, 2.18)	0.74 (0.00, 4.39)	1.64 (0.00, 8.66)	1.94 (0.00, 10.77)	2.24 (0.00, 12.46)
AFR D	0.92 (0.00, 4.96)	0.36 (0.00, 2.11)	0.74 (0.00, 4.34)	1.66 (0.00, 8.64)	1.94 (0.00, 10.77)	2.28 (0.00, 12.53)
AFR E	0.93 (0.00, 5.08)	0.37 (0.00, 2.20)	0.74 (0.00, 4.44)	1.61 (0.00, 8.72)	1.92 (0.00, 10.76)	2.61 (0.00, 14.44)
America (AMR)	0.68 (0.00, 3.48)	0.03 (0.00, 0.10)	0.52 (0.00, 3.24)	1.46 (0.00, 7.88)	1.88 (0.00, 9.67)	2.26 (0.00, 11.67)
AMR A	0.09 (0.00, 0.34)	0.01 (0.00, 0.05)	0.05 (0.00, 0.17)	0.17 (0.00, 0.61)	0.25 (0.00, 0.89)	0.41 (0.00, 1.39)
AMR B	0.99 (0.00, 5.11)	0.37 (0.00, 2.22)	0.75 (0.00, 4.48)	1.71 (0.00, 8.90)	2.04 (0.00, 11.02)	2.58 (0.00, 13.17)
Middle East (EMR)	0.92 (0.00, 4.67)	0.36 (0.00, 1.98)	0.77 (0.00, 4.16)	1.69 (0.00, 8.16)	2.06 (0.00, 10.41)	2.49 (0.00, 11.91)
EMR B	0.91 (0.00, 4.99)	0.35 (0.00, 2.11)	0.72 (0.00, 4.36)	1.59 (0.00, 8.64)	1.91 (0.00, 10.72)	2.19 (0.00, 12.24)
EMR D	0.94 (0.00, 4.62)	0.36 (0.00, 1.84)	0.78 (0.00, 4.08)	1.72 (0.00, 8.12)	2.10 (0.00, 10.37)	2.65 (0.00, 11.91)
Europe (EUR)	0.99 (0.00, 2.93)	0.63 (0.00, 1.82)	0.94 (0.00, 2.78)	1.42 (0.00, 4.23)	1.58 (0.00, 4.70)	1.73 (0.00, 5.18)
EUR A	0.96 (0.00, 2.81)	0.56 (0.00, 1.64)	0.90 (0.00, 2.66)	1.43 (0.00, 4.22)	1.64 (0.00, 4.93)	1.80 (0.00, 5.37)
EUR B	1.02 (0.00, 3.04)	0.69 (0.00, 2.05)	0.98 (0.00, 2.92)	1.41 (0.00, 4.21)	1.53 (0.00, 4.58)	1.66 (0.00, 4.98)
EUR C	1.00 (0.00, 2.99)	0.67 (0.00, 1.98)	0.97 (0.00, 2.88)	1.39 (0.00, 4.16)	1.52 (0.00, 4.54)	1.64 (0.00, 4.92)
Southeast Asia (SEAR)	0.77 (0.00, 2.81)	0.27 (0.00, 0.99)	0.60 (0.00, 2.06)	1.41 (0.00, 6.01)	1.83 (0.00, 7.71)	2.17 (0.00, 9.46)
SEAR B	0.93 (0.00, 5.08)	0.37 (0.00, 2.20)	0.74 (0.00, 4.44)	1.61 (0.00, 8.72)	1.92 (0.00, 10.76)	2.61 (0.00, 14.44)
SEAR D	0.68 (0.00, 2.44)	0.26 (0.00, 0.95)	0.57 (0.00, 1.85)	1.26 (0.00, 4.62)	1.64 (0.00, 6.27)	2.03 (0.00, 8.37)
Western Pacific (WPR)	2.03 (0.00, 6.56)	0.40 (0.00, 1.78)	1.40 (0.00, 5.00)	4.46 (0.00, 13.85)	6.15 (0.00, 18.48)	7.38 (0.00, 22.16)
WPR A	0.88 (0.00, 2.70)	0.33 (0.00, 1.06)	0.76 (0.00, 2.29)	1.59 (0.00, 4.79)	1.94 (0.00, 5.92)	2.27 (0.00, 7.41)
WPR B	2.12 (0.00, 6.84)	0.42 (0.00, 1.89)	1.45 (0.00, 5.22)	4.61 (0.00, 14.24)	6.27 (0.00, 18.88)	7.89 (0.00, 23.76)
World	**1.10 (0.00, 4.13)**	**0.28 (0.00, 1.29)**	**0.78 (0.00, 3.31)**	**1.96 (0.00, 8.11)**	**2.66 (0.00, 10.44)**	**3.75 (0.00, 13.46)**

Table 6
Estimated median (95% uncertainty interval) Disability-Adjusted Life Years by World Health Organization region.

Region	Mild ID	Moderate ID	Severe ID	Profound ID	Total	Total per 100,000
Africa (AFR)	784,915 (0–6,349,387)	54,495 (0–565,499)	1619 (0–20,493)	0.6 (0–9)	841,085 (0–6,935,387)	85 (0–698)
AFR D	380,688 (0–3,005,988)	26,585 (0–267,165)	793 (0–9664)	0.3 (0–4)	407,886 (0–3,282,822)	86 (0–690)
AFR E	397,676 (0–3,351,344)	27,534 (0–298,872)	815 (0–10,841)	0.3 (0–5)	426,026 (0–3,661,062)	82 (0–707)
America (AMR)	387,829 (0–2,936,837)	27,675 (0–293,105)	879 (0–12,145)	0.3 (0–5)	417,488 (0–3,219,973)	42 (0–328)
AMR A	15,913 (0–75,960)	1069 (0–5825)	31 (0–185)	0.009 (0–0.06)	17,013 (0–81,979)	5 (0–22)
AMR B	314,699 (0–2,381,777)	23,195 (0–250,450)	717 (0–10,154)	0.2 (0–4)	337,780 (0–2,614,618)	64 (0–499)
AMR D	56,851 (0–479,100)	3936 (0–42,726)	117 (0–1550)	0.04 (0–0.6)	60,904 (0–523,376)	67 (0–573)
Middle East (EMR)	453,372 (0–3,438,860)	31,491 (0–303,831)	935 (0–10,931)	0.3 (0–4)	485,753 (0–3,753,678)	75 (0–576)
EMR B	98,160 (0–823,918)	6795 (0–73,443)	201 (0–2663)	0.06 (0–1)	105,156 (0–900,026)	57 (0–491)
EMR D	352,431 (0–2,614,941)	24,481 (0–230,423)	730 (0–8284)	0.2 (0–3)	377,626 (0–2,853,652)	81 (0–609)
Europe (EUR)	389,541 (0–1,505,684)	27,124 (0–118,296)	807 (0–3871)	0.2 (0–1)	417,472 (0–1,627,853)	46 (0–178)
EUR A	170,794 (0–664,011)	11,882 (0–52,130)	353 (0–1704)	0.1 (0–0.5)	183,029 (0–717,930)	41 (0–162)
EUR B	125,647 (0–484,299)	8755 (0–38,141)	261 (0–1250)	0.08 (0–0.4)	134,663 (0–523,690)	57 (0–223)
EUR C	92,676 (0–356,828)	6453 (0–28,025)	192 (0–917)	0.06 (0–0.3)	99,321 (0–385,771)	42 (0–164)
Southeast Asia (SEAR)	860,332 (0–4,548,837)	59,280 (0–375,490)	1752 (0–12,887)	0.6 (0–5)	921,355 (0–4,969,327)	48 (0–258)
SEAR B	169,320 (0–1,426,912)	11,723 (0–127,252)	347 (0–4616)	0.1 (0–2)	181,390 (0–1,558,782)	52 (0–449)
SEAR D	689,816 (0–3,178,510)	47,398 (0–255,708)	1397 (0–8525)	0.5 (0–3)	738,578 (0–3,446,492)	47 (0–218)
Western Pacific (WPR)	1,902,959 (0–9,171,047)	142,023 (0–962,315)	4475 (0–40,057)	1 (0–18)	2,051,371 (0–10,188,939)	110 (0–544)
WPR A	50,793 (0–206,102)	3521 (0–16,332)	104 (0–541)	0.03 (0–0.2)	54,419 (0–222,722)	34 (0–137)
WPR B	1,855,000 (0–8,976,526)	138,274 (0–945,695)	4377 (0–39,494)	1 (0–17)	1999,995 (0–9,978,877)	117 (0–584)
World	**4,882,296 (0–28,005,953)**	**356,676 (0–2,648,051)**	**10,888 (0–102,481)**	**4 (0–43)**	**5,243,184 (0–30,790,070)**	**71 (0–420)**

levels are lower in just about all commonly consumed foods, including vegetables and cereals consumed in large amounts.

When compared to estimates for blood lead values throughout the world (see Table 1 in World Health Organization, 2011), the proportion of total lead exposure attributable to dietary lead varies tremendously. In some parts of the world (particularly Cameroon, Chile, China), food appears to account for the majority of exposure to lead. At the other end of the spectrum, exposure from lead in food appears to be a minor contributor to blood lead levels in India, New Zealand, and the U.S. The relative contributions of the exposure routes covering the remaining intakes are currently unclear and warrant further investigation.

It is also worth noting that dietary lead exposure is monitored much more closely in some parts of the world than others. While countries in Europe, North America, and the Western Pacific regions are all well represented in the total diet study literature, reports from other parts of the world are sparse to nonexistent. While the global estimates for IQ decrements and DALYs presume that dietary lead exposures are assumed to fall in the same range as the rest of the world, it is quite possible that some areas are higher. The estimate for India that is based on a single market study city (Mumbai) is especially worth calling into question. Since India is in a region with the highest blood lead levels in the world (World Health Organization, 2011; Ericson et al., 2018), a better survey is highly desirable. Similarly, but with the opposite concern, the estimate for Chile is based on a single city study that produced dietary intake estimates for lead that are unusually high.

While the calculations with the linear disability weight function do not use the World Health Organization (2017) disability weights as they were intended, they do indicate that social evaluation of the impact of IQ can be evaluated as a continuous function that does not require binning into disease categories. In particular, while the discontinuous DALY evaluation does not assign any valuation on individuals with above average IQ, the continuous function does. Although the estimates obviously depend on the valuation function, the continuous interpretation of the World Health Organization (2017) values used here indicates that a continuous function may yield estimates that are not greatly dissimilar to those obtained by binning.

5. Conclusion

Dietary exposure to lead occurs throughout the world. Dietary exposure to lead is relatively well characterized in Europe, North America, and the Pacific Rim by total diet studies designed to be nationally representative. However, studies conducted elsewhere are few and far between. Based on the available evidence and a dose-response characterization previously developed by WHO and FAO, average IQ decrements ranged from 0.09 in North America to 2.12 in Western Pacific B. The global average IQ decrement attributable to dietary lead was 1.1. It should be noted that there was considerable uncertainty associated with these estimates, which arose from both the exposure and dose-response portions of the risk assessment. The total number of DALYs arising from those IQ decrements was estimated to be 5.2 million DALYs, with an uncertainty range of 0–31 million DALYs.

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Competing interests

The authors declare they have no actual or potential competing financial interests.

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