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RESEARCH ARTICLE

Bovine lead exposure from informal battery recycling in India

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Abstract
We provide an estimate of annual bovine lead exposure and attributable mortality at informal lead acid battery recycling sites in India. We use Pure Earth's Toxic Sites Identification Program database, the FAO's Gridded Livestock dataset, and a Poisson plume model of lead particle air dispersion to estimate site-level mortality. We calculate that India suffers 2370 excess bovine fatalities each year, resulting in more than USD $2.1 million of economic damage. The distribution of damages by location is highly skewed. While we find most sites (86.3%) induce no mortalities, 6.2% of sites induce minor damage (1 to 5 fatalities), 4.1% induce moderate damage (6 to 20 fatalities), and 3.4% induce severe damage (21 + fatalities). These findings highlight the importance of geospatial data to prioritize mitigation efforts and identify a previously unquantified burden on the rural poor.

Keywords Soil pollution · Lead recycling · Geospatial distribution · Lead livestock exposure · Low- and middle- income countries

Introduction

Lead exposure assessments generally focus on human health, but livestock exposure may also represent a considerable negative environmental externality. Lead is an essential industrial input with 85% of its application found in the manufacture of lead-acid batteries (International Lead Association 2014). Global demand for lead exceeded 10 million tonnes in 2014 with more than half being met through secondary smelting (i.e., recycling) (International Lead Association 2014). In low- and middle-income countries (LMICs), much of this recycling takes place in the under-regulated informal sector, characterized by little or no environmental controls and often occurring in residential areas (World Health Organization 2017). Assessments of environmental contamination carried out near recycling sites in LMICs consistently find levels considered highly hazardous to human health. Further, the persistence of lead in soil implies a long-lasted agricultural economic damage, as soil provides natural capital and ecosystem services to an economy (Dominati et al. 2010). Daniell et al. (2015) identified mean soil lead concentrations of 2500 mg/kg in a Vietnamese battery recycling village, more than 6 times the applicable US Environmental Protection Agency (USEPA) screening level (USEPA 2001). In Senegal, investigators identified residential soil levels as high as 300,000 mg/kg (30% lead) (Haefliger et al. 2009).

India is one of the world's larger secondary producers of lead, having recycled more than 34,100 tons in 2012 (Varshney et al. 2020). It also has an extensive informal used lead acid battery (ULAB) recycling sector, which the India Lead Zinc Association estimates may comprise 25 to 40% of lead recycling in the country (International

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Highlights
• Lead acid battery recycling sites in India pollute nearby soils.
• We estimate 2370 annual bovine deaths are the result of this pollution.
• Annual damages are valued at approximately US$2.1 million.
• Without remediation efforts, these damages would repeat each year.
• This exercise identifies additional remediation decision factors.

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2019; Singal 2021) (see Fig. 1 for images of an abandoned ULAB site). Lead emissions can affect India's agricultural products, as documented in Kolkata (Mukherjee et al. 2013), and India's livestock, as argued in this paper. India is home to the world's largest population of bovine, with more than 302 million cattle identified in the most recent census (Department of animal husbandry and dairyings 2012). The livestock sector holds an important place in India's economy as livestock production is estimated to contribute 4% of India's GDP and as much as 70% of rural employment (Roy and Singh 2013).

In this study, we combine Global Information System (GIS) data from the Food and Agriculture Organization of the United Nations (FAO) on bovine livestock density with soil pollution mapping conducted by the NGO Pure Earth to estimate the extent of bovine livestock lead exposure and attributable mortality in India. Specifically, we model exposure frequency and severity according to bovine density and soil lead concentrations, then estimate the number of attributable deaths with their costs, as determined by market prices. Lead particles are highly immobile in soil, tending to remain near the surface for prolonged periods (Federal Round Table 2020). This can pose a continuous potential risk to grazing cattle, which ingest from 1 to nearly 18% of their dry matter intake as soil (Thornton and Abrahams 1983).

Accordingly, the soil intake pathway represents a significant source of bovine lead exposure (Mayland et al. 1975; Alloway 2012; McDowell 2003; Sharpe 2004). General symptoms of bovine lead poisoning include blindness, convulsions, aggression, teeth grinding, respiratory failure, and in some cases, death (Blakley 1984; Zmudski et al. 1983; Bates and Payne 2017).

Despite toxicological evidence, documented cases, and the potential for harmful livelihood impacts, we are not aware of any studies that have attempted to quantify the mortality and associated economic costs of bovine lead exposure in India. Given the large role livestock plays in the rural Indian economy, especially as a provider of rural employment (Roy and Singh 2013), the environmental damage from the pollution at these sites to local livestock represents a previously unquantified burden for the rural poor. Poorer households generally depend more on livestock than richer households. Farmers holding less than 0.01 hectares of land earned 26% of their income from animal husbandry compared to 6% with farmers holding over 10 hectares (Chakravorty et al. 2019). In non-migrating families, livestock ownership was an important source of livelihood diversification for households in the lower half of the income distribution (Deshingkar et al. 2020).

We find (in the 146 sites with detailed soil lead data included in this study) that lead exposure leads to 294 bovine deaths each year. Extrapolating this number to all of India, which is estimated to have 1177 informal ULAB sites (Ericson et al. 2016), implies that residual lead in the soil at these sites is responsible for 2370 excess bovine deaths each year.

The economic damages from bovines deaths are valued at more than USD $2.1 million. These damages would be expected to recur each year (unless clean-up efforts took place) as lead stays in the environment. We also find that the distribution of the sites that incur damages is highly skewed, with a few sites being responsible for most of the damage. Most sites (86.3%) induce no mortalities, 6.2% of sites induce minor damage (1 to 5 fatalities), 4.1% induce moderate damage (6 to 20 fatalities), and 3.4% induce severe damage (20+ fatalities). This highlights the importance of geospatial analysis along with soil testing to create priority lists of which sites should be the focus of environmental remediation efforts.

Fig. 1 Abandoned used lead-acid battery (ULAB) recycling site. *Left*: inactive lead recycling furnace. *Middle*: collection of lead dust on vegetation. *Right*: discarded lead-acid battery components. Photos taken by authors

Data

Pure earth's toxic sites identification program database

As part of their Toxic Sites Identification Program (TSIP) (PureEarth 2020), Pure Earth recorded geo-located soil lead concentrations surrounding 146 informal ULAB recycling sites in India. Trained Pure Earth investigators used field portable X-ray fluorescence (pXRF) spectrometry to quantify in situ surface soil lead concentrations at these sites (Ericson et al. 2013).

Food and Agriculture Organization's (FAO) Gridded Livestock database

The FAO gridded livestock data are available at a spatial resolution of 3 min of arc (about 5 × 5 km at the equator). These data are initially based on nationally reported livestock statistics and observed livestock densities, then expanded with statistical modeling and adjusted according to corroborating datasets from FAOSTAT and elsewhere (Robinson et al. 2014).

Methodology

Livestock densities at ULAB sites

To determine the number of bovine grazing on lead contaminated land in India, we overlaid the FAO gridded livestock data for 2010 (most recent available year) (Robinson et al. 2014) with soil lead concentrations collected by the Pure Earth. Figure 2 depicts the bovine densities for India overlaid with the TSIP ULAB lead contamination sites. Information about the GIS methods used is available in Appendix A.1.

Modeling the area of lead exposure based on soil readings

Because the Pure Earth TSIP database utilizes a limited number of surface soil measurements, it does not necessarily map a comprehensive characterization of soil contamination at each of the 146 sites in India. To interpolate surface soil lead levels, we modeled the likely spatial attenuation of soil lead concentrations (to understand how lead pollution levels decay moving away from the centroid of the pollution site) at each of the 146 sites.

Spatial attenuation

Each of the 146 ULAB sites has Global Positioning System (GPS)-tagged soil lead samples, which allowed us to obtain exact distances in meters between samples. We assumed the highest recorded value at each site was the site's center. We then measured the distance of each other sample taken at the site to the center point. Thus, each site had a center point and a set of samples with unique distances from the center. In total, the database provided 770 soil lead points for India ULAB sites, or approximately 5 samples per site. See a graphical depiction of this process in Fig. 3.

We empirically estimated how lead pollution level decay moving away from the source point by adapting a Poisson plume diffusion equation (Eq. 1). The Poisson plume model is derived from a Gaussian plume model, as described by Stockie (2011). Gaussian equations commonly inform industrial air-particulate dispersion modeling, as seen, for example, in the EPA's SCREEN3, CTSCREEN, RTDM3.2 models (USEPA 2021).

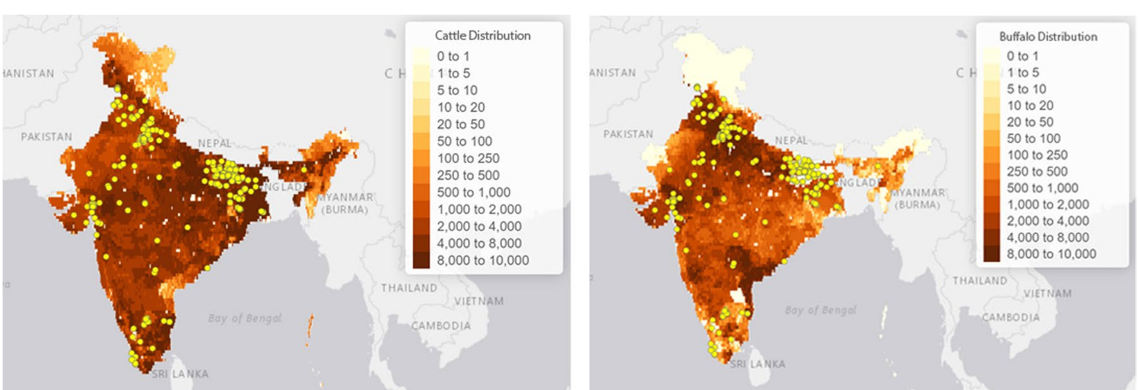

Fig. 2 FAO gridded bovine densities for India overlaid with the 146 lead contaminated sites used in the analysis

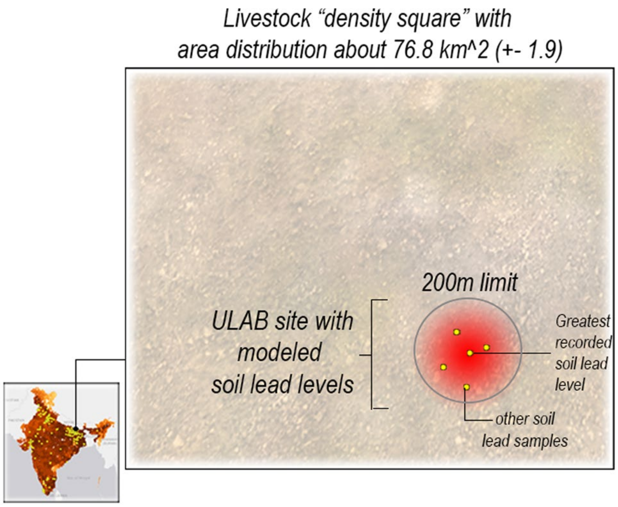

Fig. 3 Depiction of a ULAB site modeled within an FAO livestock density square. We estimated the site's total soil lead contamination with a linear model based on a Poisson plume diffusion equation (Eq. 1) using the highest measured soil lead level as the center of the site. The proportion of contaminated land to the area of the livestock density square is assumed to equal the portion of livestock potentially exposed to soil lead

$$C(x, y, z) = \frac{Q}{4K\pi}\left(\frac{1}{\sqrt{x^2 + y^2 + (z - H)^2}} + \frac{1}{\sqrt{x^2 + y^2 + (z + H)^2}}\right) \tag{1}$$

Q rate of particulate emission

K eddy diffusion coefficient

x, y, z 3-dimension distance variables from emission source

H height of emitting stack

The original Poisson plume diffusion equation is in three dimensions (providing a distribution of soil pollutant concentrations on an x-y-z plane); however, we reduced it to one dimension (the x-axis). That is, we assumed the dispersion was equally distributed across the x-y plane (we tested if wind direction influenced soil lead levels in opposite hemispheres around a source point and found that it did not, see Appendix A.2 and Table 2). We removed the z axis because measuring ground level concentrations implies $z = 0$. Another way to think about this is that we are modeling the radius of a circle emanating from the center point of the pollution source, so we can consider just one dimension. Regarding the other variables in Eq. (1), these furnaces are subterranean, so $H = 0$ (think of this as the highest point of a smokestack at ground level). The minimal influence of wind lifting and moving lead particles suggests we can follow Stockie (2011)'s example and let $K = 1$ to observe the typical behavior of the plume distribution. The model simplifies considerably to Eq. (2).

$$C(x) = \frac{Q}{4\pi}\left(\frac{1}{\sqrt{x^2}} + \frac{1}{\sqrt{x^2}}\right) \tag{2}$$

Which further simplifies to Eq. (3).

$$C(x) = \frac{Q}{4\pi}\left(\frac{2}{x}\right) = \frac{Q}{2x\pi} \tag{3}$$

Because lead emission rates and operation times were unavailable for the ULAB sites, we exploit the fact that the emission rate must be a function of both the observable highest soil lead level found at a site and an unobserved time variable (Eq. 4).

$$Q = \frac{M}{t} \tag{4}$$

Q rate of particulate emission

M maximum value at a site, also assumed to be the site's source point

t unobservable time variable

Rearranging suggests the highest soil lead level would incorporate both the emission rate and the total time of ULAB site operation (Eq. 5). That is, because the maximum value, M, of a site is the function of the emissions rate Q and time t, we argue empirical estimations of M at a given site will control for the unobserved Q and t variables.

$$M = Qt \tag{5}$$

In Eq. (3) soil lead concentrations are primarily driven by the emission rate (Q), which we argue is suitably contained in M, as well as the distance from the emission source. This implies soil lead concentrations will approach 0 as x (the distance from the source) approaches infinity, typically. However, lead soil particles may be disrupted and shifted by human activity (e.g., walking through site and tracking/carrying lead dust on shoes). Thus, our needs are better served by estimating the effects of M and distance with a linear regression. In this case, the linear coefficient for M will control for the changes in emission rate and time of operation, the coefficient for $(1/(2x\pi))$ will control for the decay of soil lead levels from the emission source including the additional concern for unobserved human actions, and the intercept will likely provide a threshold before which soil lead concentrations are negligible.

Finally, because the scatterplots of soil lead concentrations by distance (Appendix A.3) at 500 m appeared to show little deviation from 0 once past 200 m, and because the Poisson plume dispersion model levels off quickly, we decided that 200 m was the max distance one would expect lead dust to travel. Because maximum values were not normally distributed across sites, we logarithmically transformed M ($log(M)$). Equation (6) below describes the linear OLS regression used to model the soil lead concentrations at each site.

$$S = a + \beta_1\left(\frac{1}{2x\pi}\right) + \beta_2(log(M)) + e \tag{6}$$

S soil lead concentrations (mg/kg)

a intercept term

β_n linear coefficients

x linear distance from source point

M maximum value at a site, also assumed to be the site's source point

This gives us the predicted soil lead levels along a distance gradient from the emission sources (x-axis); we project the predicted soil lead levels uniformly across the horizontal distances (y-axis). This results in uniform concentric circles increasing in radius by 1 m. We tested existing TSIP data to verify that pollution appears to be equal in all directions from the source point (see Appendix A.2).

Calculating lead dose

We calculated the amount of lead ingested each day by bovine based on estimated soil lead concentrations and several assumptions about bovine body mass, grazing time, and diet. These inputs were used in the following calculation based on Johnsen and Aaneby (2019):

$$D = \frac{S * F * S_i n}{B_w} * G \tag{7}$$

where D is the lead dose per day (mg/kg body weight per day), S is the soil lead concentration (mg), F is the amount of fodder ingested per day (kg of dry weight), S_i is the daily soil ingestion rate, B_w is the body weight (kg), and G is the duration of exposure.

We predict lead concentration values (S) using Eq. (6) to form concentric circles emanating out from the ULAB site's source point of contamination at every 1 m interval. Bovine ingest fodder (F) in relationship to their body weight (B_w). A bovine ingests approximately 3% of its bodyweight in fodder each day (Birthal and Dikshit 2010; Department of Primary Industries and Regional Development 2020). Bovine soil intake ($S_i n$) ranges between 1 and 18% of total dry matter intake (Thornton and Abrahams 1983). Because India features heavy monsoon rains and more sparse grazing conditions that have been shown to increase soil intake, we use a conservative value of 10% for $S_i n$ (Thornton and Abrahams 1983). The 10% is broadly consistent with values noted elsewhere, including Siberia (Mamontova et al. 2007) where conditions were also sparse.

Finally, the duration of exposure (G) is assumed to be a function of, first, the area of exposed land in a livestock density square and, second, the amount of time bovine would spend grazing directly from that land. We assume the bovine livestock are reasonably equally distributed in the density square, so the percent of the density square area covered by contaminated land equals the percent of that square's bovine exposed. India bovine feeding practices vary. However, India is under-supplied in cultivated fodder (Turner 2004), and up to 100% of poor farmers in certain regions rely, at least partially, on grazing or common property resources (Roy and Singh 2013; Rathore et al. 2010). The reviewed literature presents a consensus that approximately 50% of farmers India-wide rely primarily on grazing their bovine livestock, both for cattle and buffalo (Kumar and Singh 2008; Turner 2004; Roy and Singh 2013; Rathore et al. 2010; Kishore 2013). Thus, we reduce lead dosage by 50% to only account for the time bovine spend directly feeding from contaminated soils.

Estimating the number of lethally exposed bovines

The number of lethally exposed bovine is represented by Eq. (8). If the contaminated soil provides a daily dose above the fatal threshold values, 6 mg/kg and 5 mg/kg for adults and calves, respectively (Zmudski et al. 1983), then we consider it an area of fatal exposure (A_E). These threshold values were also used by Johnsen and Aaneby (2019) in their ruminant soil lead exposure assessment.

$$Fatalities_i = \frac{A_{Ei}(S_o, S_i)}{A_{Ti}} * D_{ti} \tag{8}$$

The emission point of pollution at each site is assumed to be at the site's highest recorded soil sample (M). The modeled soil exposure (S) was calculated via Eq. (6). The density square area (A_{Ti}) and the density of bovine in the density square (D_{Ti}) are provided by the FAO's gridded livestock dataset (Robinson et al. 2014). Thus, we estimated the number of bovine with fatal exposure is equal to the number of bovine in the density area grazing on land containing soil with lead concentrations above the threshold values. The percentages of adult and calf bovine, of the total bovine population, were based on the most recent Indian livestock census (Department of animal husbandry and dairyings 2012). Our calculations are conservative in that we only count a bovine mortality when its daily soil intake exceeds the fatal threshold values. We do not account for potential deaths of bovines that ingest smaller amounts of lead over longer periods of time that eventually build up to a toxic level within the animal.

Estimating the monetary value of bovines

To estimate the value of cattle and buffalo at adult and calf ages, we recorded and averaged the listed price of 30 adult cattle, 26 calf cattle, 33 adult buffalo, and 18 calf buffalo of various breeds from several online markets. A data summary and sources can be found in Tables 4, 5, 6, 7, 8. We used an exchange rate of 70.49 Rupees to 1 USD (Bank 2020).

Results

Model output and bovine exposure estimates

We obtained the following OLS regression, which we used to estimate the soil lead levels in 1 m concentric circles at each site:

$$C = -8109.20 + (64700.70)\left(\frac{1}{2x\pi}\right) + (1067.80)(log(M)) \tag{9}$$

All parameters significant at 99%.
Residual std error: 5252 on 767 degrees of freedom.
$R^2 = 0.1207$

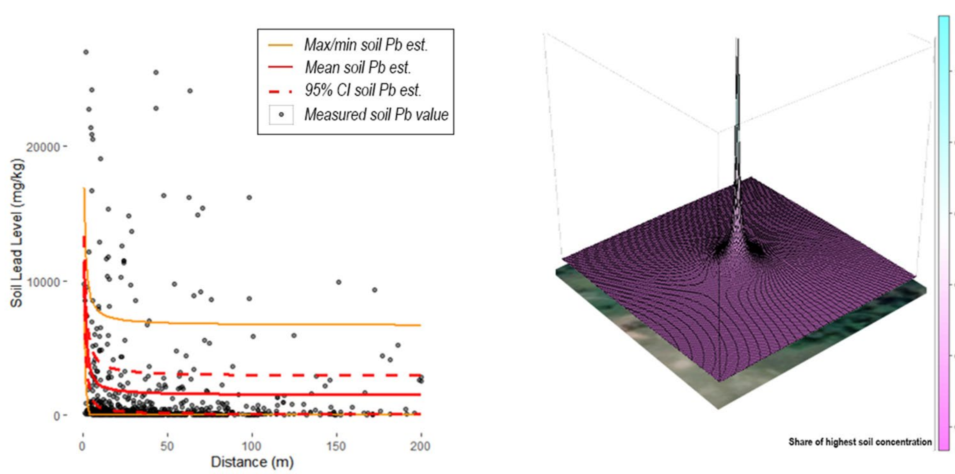

Fig. 4 *Left*: the actual soil lead level data with the linear OLS regression outcomes, with min, max, and 95% CI, at each site in one dimension. *Right*: an example of a three-dimension projection of the soil modeling outcome at a given site. Both the height of the curve and the color represent the relative soil lead values emanating out from the highest recorded soil lead point

Table 1 Count and cost of bovine fatalities in Rs and USD. Bovine values were identified from 2021 market prices as seen in Tables 4, 5, 6, 7, 8

Type	Unit value Rs (USD)	Fatalities	Totals Rs (USD)
Buffalo	67,245.10 Rs ($956.54)	151	10,154,009.80 Rs ($144,438)
Adult	90,606.06 Rs ($1,288.85)	88	7,973,333.33 Rs ($113,418.68)
Calf	24,416.67 Rs ($347.32)	63	1,538,250.00 Rs ($21,881.22)
Cattle	59,116.41 Rs ($840.92)	144	8,453,646.73 Rs ($120,251.02)
Adult	75,450.63 Rs ($1,073.27)	93	7,016,908.90 Rs ($99,813.78)
Calf	40,269.23 Rs ($572.82)	50	2,013,461.54 Rs ($28,640.99)
			18,607,656.54 Rs ($264,689.28)

See Table 3 for full regression output.

A description of the single dimension distribution of estimated soil lead levels is provided in Fig. 4, along with an example of the distribution projected in two dimensions. Full OLS regression outputs can be seen in Appendix A.3

Bovine fatalities and area of exposure

We estimate that 2322 bovine spend half their time grazing within 200 m of the source point for the 146 ULAB sites. Our subsequent estimates for annual bovine fatalities are provided in Table 1. We find an aggregate of 294 annual bovine fatalities across the 146 sites, with a per site average of 2.01 (95% CI [1.32, 2.68]) and a median of 0.0039 (min of 0; 25th percentile of 0.001; 75th percentile of 0.003; max of 73.727). These fatalities suggest a 12.66% lead-related mortality rate among this sub-population. The 294 fatalities comprised 93 adult cattle, 88 adult buffalo, 50 calf cattle, and 63 calf buffalo. The aggregate area of soil contamination contributing to lethal levels of lead exposure is 2.59 km^2 (per site min: ≈ 0 km^2; per site max: 0.13 km^2).

Cost of bovine fatalities

The costs of bovine fatalities calculated using market prices are listed in Table 1.

Distribution of bovine fatalities

The distribution of deaths by location is highly skewed, meaning that a minority of sites produce a majority of deaths (Fig. 5). Most sites (86.3%) induce no mortalities, 6.2% of sites induce minor damage (1 to 5 fatalities), 4.1% induce moderate damage (6 to 20 fatalities), and 3.4% induce severe damage (21+ fatalities). The distribution of damages by location shows why geospatial data is important in this context as it allows for prioritizing mitigation at ULAB sites where damages are more severe.

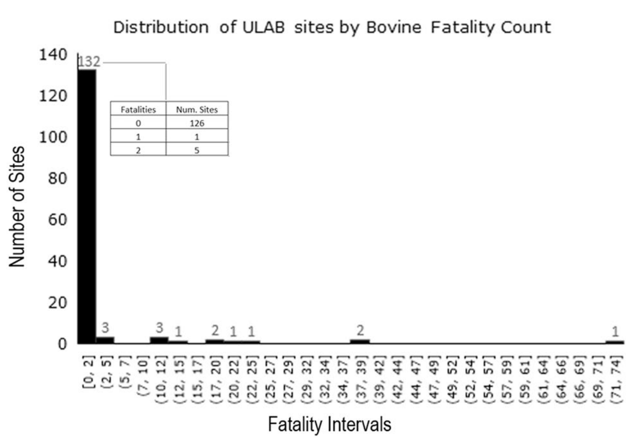

Fig. 5 Approximately 86.3% (126/146) of sites are responsible for zero fatalities, 6.2% (9/146) of sites induce minor damages (1 to 5 fatalities), 4.1% (6/146) induce moderate damages (6 to 20 fatalities), and 3.4% (5/146) induce severe damages (21 + fatalities)

Estimating economic damage country-wide

Thus far, we have focused on the 146 ULAB sites with soil data in the TSIP dataset. A policy-relevant extension is to consider the economy-wide effects of bovine mortality due to lead ingestion at ULAB sites. A 2016 study calculated the number of informal ULAB sites in each of 90 LMICs based on factors such as the amount of lead circulating in each country and the approximate size of the informal sector (Ericson et al. 2016). For India, the authors calculated a low-end estimate of 1177 informal ULAB sites that are similar in composition to those presented in this study (Ericson et al. 2016). Thus, if we assume the bovine exposures at these 146 sites are analogous to those 1177 sites, we can calculate a national estimate for bovine deaths and economic damage at ULAB sites.

We estimate that India faced 2370 excess bovine mortalities in per year (749 adult cattle, 709 adult buffalo, 403 calf cattle, 347 calf buffalo) resulting in more than USD $2.1 million of economic damage. Further, nationwide we expect 48 sites induce minor damages (1 to 5 fatalities), 72 induce moderate damages (7 to 20 fatalities), and 48 induce severe damage (greater than 20 fatalities). It is likely this nationwide estimate is conservative for at least two reasons. First, we used the lower end estimate for the number of ULAB sites from the 2016 study, and second, we expect that ULAB sites have increased in the country since 2016 given the high worldwide demand for lead.

Discussion

Previous literature suggests that our estimates are both realistic and conservative. In their study of ruminants grazing on lead-contaminated soil, Johnsen and Aaneby (2019) found no mortality risk for cattle or sheep grazing on soil contaminated up to 3700 mgPb/kg. Our estimates are very near theirs as our estimates suggest zero bovine fatalities up to 3333 mgPb/kg for calves and 4000 mgPb/kg for adults. However, our results are more conservative than a study performed at a Brazilian lead battery recycling plant. Lemos et al. (2004) investigated lead exposure in a herd of 120 Nelore cows and found that 35 died within 45 days with clinical signs of cortical neurological disturbances. The measured soil lead concentrations in the pasture area were 147–431 mgPb/kg (Lemos et al. 2004), which are a much lower concentration to cause mortality than in our study. This suggests that our results are conservative estimates.

Previously documented cases of livestock lead exposure in India lend further credence to our expected number of bovine fatalities. Studies of Indian livestock morbidity and mortality in Karnal (Prasad et al. 2004), Maharashtra (Bangar et al. 2013), Himachal Pradesh (Chaudhary et al. 2013), and Haryana (Pal et al. 2018) have suggested all-cause bovine mortality rates of 14.17%, 4.42%, 9.14%, and 2.56%, respectively. Our model suggests that lead poisoning provides an additional bovine mortality burden of 12.61% among bovine grazing within 200 m of a ULAB site. Note that our estimates only assume death if a bovine encounters a fatal lead dose in a given year. We do not account for gradual lead exposure over multiple years at smaller doses that eventually reach a fatal threshold of total cumulative exposure.

Unfortunately, there appears no easy policy solution for ULAB lead exposure among livestock. At any given ULAB site, eliminating soil lead exposure requires active (and costly) remediation by engineers. Lead's persistence in soil implies that shutting down ULAB sites will not resolve the soil-lead exposure problem. Additionally, because of low barriers to entry and the low level of capital necessary to smelt lead (as evidenced by the number of impoverished people engaged in the activity, the process's crudeness, and the general lack of safety equipment (PureEarth 2020)), new sites can open relatively quickly. Only closing current ULAB sites without enacting systemic changes may promote their reopening elsewhere and increase the total area of contaminated soil. As the area of exposure increases, the area on which farmers could safely forage for fodder or graze livestock shrinks. Policy makers might consider designing incentives to register ULAB sites and protective regulations to contain site exposure areas such as fencing to prevent livestock from entering ULAB sites.

Yet, if the affected farmers have little political influence and the overall contribution to the total bovine mortality rate is perceived as low, policy makers may not be driven to act at all.

While providing site-specific contamination and mortality rates for the 146 sites in the TSIP dataset and an India-wide estimate, this study has some limitations and likely is a conservative estimate. First, it only models the costs related to animal mortality, but not morbidity. Modeling based on lethal daily dose largely precludes measuring cumulative exposure or non-lethal negative health outcomes (lost milk productivity, birth defects). Some evidence suggests lead has negative reproductive effects even on male ruminants (Guvvala et al. 2020). Recent studies have observed adverse symptoms at even relatively low soil lead concentrations (Abrahams and Thornton 1994; Aslani et al. 2014; Cowan and Blakley 2016; Ikenaka et al. 2012; Krametter-Froetscher et al. 2007; Thornton and Abrahams 1983; Zadnik 2010). Cowan and Blakley (2016) found euthanization was the most effective option for lead-poisoned cattle in Canada given the recovery rates, product contamination, and medical costs. This suggests that the non-fatality-related health outcomes are likely large and important. Second, because the FAO livestock density maps are not available past 2010, it is difficult to make year-to-year estimates up to the present date, especially if the geographic distributions of livestock densities have changed drastically since 2010. Therefore, while we believe this estimate is useful, we suggest caution because the livestock density data is dated, and informal battery recycling is an active and growing industry. Finally, we limit our lead exposure to that of soil uptake via grazing. It is presumably possible that grasses collected by farmers and brought to bovines as fodder could provide further exposure.

There remain many avenues for future study. First, similar concerns for lead exposure in other ruminants (such as sheep or goats) have been documented. Expanding the study to include estimates concerning the number of fatalities for these species would be useful, especially as the poorest farmers are more likely to own sheep or goats rather than cattle or buffalo. Second, as humans consume livestock and livestock products, there is reason to investigate livestock products as a potential lead exposure pathway. The degree to which these livestock products (milk) are consumed locally represents an additional (and unequal) burden for the rural poor due to the externalities of recycling lead acid batteries. Third, a broader economic analysis of ULAB recycling's market size would indicate the total value of externalities per battery produced. This could help policy makers determine appropriate taxes, permits, compensations, battery buy-back programs, or other pollution reduction strategies. Fourth, because a minority of sites cause most fatalities, geographic targeting of mitigation activities is necessary. Modeling exercises like the one performed in this study could rank sites by expected mortality to prioritize mitigation investments and focus on the largest externalities. To this effect, bovine lead exposure can serve as a biomarker for human exposure (Liu et al. 2020), so measuring bovine exposure could indicate potential human exposure. Finally, in the process of providing bovine exposure estimates, we produced an empirically derived model of ULAB soil lead contamination that could serve as a framework for modeling other ULAB pollutants and damages.

Appendix

Additional methods

Appendix A.1. GIS methods

We used the coordinate reference system (CRS): "+proj=utm +zone=44 +datum=WGS84+units=m+no defs" for all GIS data. The TSIP dataset was provided a CRS with the sf package (Pebesma 2018). The cattle and buffalo gridded livestock raster shapefile (Robinson et al. 2014) was imported with the raster package (Hijmans 2019) and was vectorized using the spex (Sumner 2019) package. The sf package was also used to get the size of each density area (in squared kilometers). The sf package attributed each TSIP ULAB site with its respective cattle or buffalo density. All maps were generated with the tmap package (Tennekes 2018). The 3-D visualization of lead dispersion was created with the lattice package (Sarkar 2008).

Appendix A.2. Wind direction methods

Because lead exposure from ULAB recycling is at least partially airborne, we felt it prudent to test wind direction on soil lead level distribution. However, we found no statistically significant evidence that wind direction influenced the distribution of lead in the soil. Three sites in the TSIP database permitted radial testing because they had been sampled in a near 360° radius around several localized concentrations within each site.

We prepared a total of eight different localized source points and assumed that if the distribution of lead in the soil followed a wind direction, then the mean soil lead level would be greater in one hemisphere at any given source point. To test this, we performed *t*-tests at each of the eight local source points, among the three sites, to compare the mean soil lead values between hemispheres. As seen in Table 2, the vast majority of hemisphere tests were statistically insignificantly different from the opposite hemisphere at the 95% CI level.

Table 2 *t*-tests comparing the soil lead distributions between north–south and west–east hemispheres around 8 localized source points at three different ULAB sites. Only the west–east comparison of source point 63 was found as significantly different, which was not enough to justify including wind direction in the spatial attenuation modeling

Dong Mai					
Source point 63					
North–south comparison:	$t = -0.30$,	$p = 0.76$	CI 95% = (−10,578.42, 7912.02),	Avg north = 5506.6,	Avg south 6839.8
West–east comparison:	$t = -2.30$,	$p = 0.03$	CI 95% = (−13,145.15, −599.14),	Avg west = 1358.57,	Avg east 8230.722
Source point 224					
North–south comparison:	$t = -0.36$,	$p = 0.71$	CI 95% = (−2894.89, 2020.61),	Avg north = 1761.09,	Avg south 2198.23
West–east comparison:	$t = 0.83$,	$p = 0.43$	CI 95% = (−3432.58, −7400.86),	Avg west = 3435.4,	Avg east 1451.26
Source point 128					
North–south comparison:	$t = 0.55$,	$p = 0.60$	CI 95% = (−1322.18, 2208.02),	Avg north = 2576.27,	Avg south 2133.35
West–east comparison:	$t = -0.81$,	$p = 0.45$	CI 95% = (−3039.57, 1543.53),	Avg west = 2173.78,	Avg east 2921.80
Source point 25					
North–south comparison:	$t = -1.09$,	$p = 0.28$	CI 95% = (−16,425.33, 5001.27),	Avg north = 3058.23,	Avg south 8770.26
West–east comparison:	$t = -1.10$,	$p = 0.06$	CI 95% = (−18,671.53, 711.46),	Avg north = 1079.74,	Avg south 10,059.77
Tegal					
Source point 156					
North–south comparison:	$t = -1.54$,	$p = 0.13$	CI 95% = (−2821.83, 352.58),	Avg north = 3721.42,	Avg south 4956.04
West–east comparison:	$t = 0.60$,	$p = 0.55$	CI 95% = (−1220.96, 2258.83),	Avg north = 4494.89,	Avg south 3975.96
Source point 410					
North–south comparison:	$t = -1.36$,	$p = 0.18$	CI 95% = (−7612.29, 1494.83),	Avg north = 4059.27,	Avg south 7118.00
West–east comparison:	$t = 1.00$,	$p = 0.32$	CI 95% = (−2175.71, 6499.34),	Avg west = 6497.06,	Avg east = 4335.24
Source point 1450					
North–south comparison:	$t = 1.98$,	$p = 0.05$	CI 95% = (−8.00, 5461.26),	Avg north = 5441.20,	Avg south 2714.58
West–east comparison:	$t = -0.04$,	$p = 0.97$	CI 95% = (−3620.43, 3468.62),	Avg north = 4554.39,	Avg south 4630.30
Cinangka					
Source point 156					
North–south comparison:	$t = 0.51$,	$p = 0.61$	CI 95% = (−6646.48, 10,898.95),	Avg north = 13,646.00,	Avg south 11,519.77
West–east comparison:	$t = -0.40$,	$p = 0.75$	CI 95% = (−96,813.28, 89,364.53),	Avg north = 9145.00,	Avg south 12,869.38

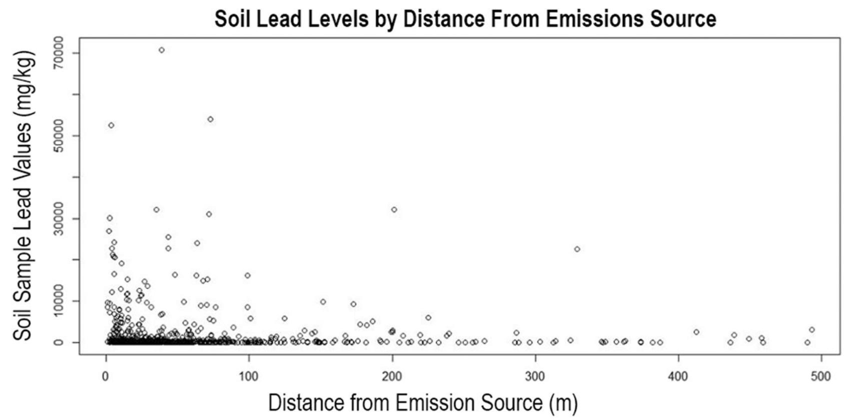

Fig. 6 Scatterplots of soil level by distance for TSIP site lead samples. A scatter plot of 4397 global points of soil level by distance

Table 3 OLS regression outputs (from Eq. 6)

Coefficients				
Variable	Estimate	Std error	*t*-value	*p*-value
Intercept	−8109.2	1104.6	−7.341	***
log(M)	1067.8	123.5	8.646	***
$(1/(2x\pi))$	64700.7	13782.3	4.694	***

Signif. codes: *** < 0.001; ** < 0.01; * < 0.05

Residuals: min: −7887; 1Q: −2177; median: −979; 3Q: 561; Max: 66,757

Residual standard error: 5252 on 767 degrees of freedom Multiple R-squared: 0.1207, adjusted R-squared: 0.1184

F-statistic: 52.65 on 2 and 767 DF, p-value: < 2.2e − 16

Table 2

Therefore, we excluded the wind direction from our main analysis.

Appendix A.3. Spatial attenuation

We anticipated that the distribution of soil lead levels would remain relatively constant for the first few meters before quickly dropping to lower values and decaying to zero at a slower rate. That is, the soil-lead levels would remain high for a short distance from the source point before dropping off quickly and flattening towards zero. This can be seen in the scatterplots of soil lead values by distance from the source point (Fig. 6)

Fig. 6

We used a linear model derived from a Poisson plume dispersion model provided in Stockie (2011) as described in the "Methods" section of the main text. We felt performance would not necessarily improve with the inclusion of sites outside of India and restricted our test to only the 146 sites in India (providing 770 soil samples). We only used the Indian sample because of variation in the parameters of each of PureEarth's TSIP country sampling resources (different funding availabilities, available technical capacity, and project management oversight meant different levels of quality and quantity in sampling in each country)

Table 3

Appendix A.4. Livestock market values

The livestock market values used in the cost calculations are in Tables 4, 5, 6, 7. Table 8 includes the website for each source of livestock market data

Table 4 Adult cattle prices

Type	Breed	Gender	Age	Year	Single	Low	High	Website
Cattle	Sahiwal	Female	Adult	2021	540,500	80,000	1,001,000	1
Cattle	Kankrej	Female	Adult	2021	50,000	40,000	60,000	1
Cattle	Red cindhi	Female	Adult	2021	60,000	50,000	70,000	1
Cattle	Kapila	Female	Adult	2021	40,000	40,000		1
Cattle	Black sahiwal	Female	Adult	2021	62,500	45,000	80,000	1
Cattle	Hf	Female	Adult	2021	55,000			1
Cattle	Jersey	Female	Adult	2021	45,000			1
Cattle	Hf	Female	Adult	2021	45,000			1
Cattle	Rathi	Female	Adult	2021	80,000			1
Cattle	Ayrshire	Female	Adult	2021	60,000			1
Cattle	Sahiwal	Female	Adult	2021	70,000			1
Cattle	Gir	Female	Adult	2021	30,000	20,000	40,000	1
Cattle	Holstein heifers	Female	Adult	2021	53,019			1
Cattle	Gir	Female	Adult	2021	200,000	100,000	300,000	1
Cattle	Ayrshire	Female	Adult	2021	60,000			1
Cattle	Gir	Female	Adult	2021	70,000			1
Cattle	Gir	Female	Adult	2021	30,000			1
Cattle	Hf jersey	Female	Adult	2021	40,000			1
Cattle	Rathi	Female	Adult	2021	80,000			1
Cattle	Hf	Female	Adult	2021	50,000	40,000	60,000	1
Cattle	Sahiwal	Female	Adult	2021	50,000			1
Cattle	Hf	Female	Adult	2021	45,000			1
Cattle	Gir	Female	Adult	2021	40,000			1
Cattle	Jersey	Female	Adult	2021	55,000			4
Cattle	Gir	Female	Adult	2021	65,000			5
Cattle	Gir kabri	Female	Adult	2021	45,000			5
Cattle	Gir cow	Female	Adult	2021	45,000			5
Cattle	Gir	Female	Adult	2021	90,000			5
Cattle	Tharparker	Female	Adult	2021	50,000	35,000	65,000	8
Cattle	Holstein friesian	Female	Adult	2021	57,500	35,000	80,000	8

Table 5 Adult buffalo prices

Type	Breed	Gender	Age	Year	Single	Low	High	Website
Buffalo	Murrah	Male	Adult	2021	80,000			2
Buffalo	Murrah	Male	Adult	2021	40,000			2
Buffalo	Haryana murrah	Female	Adult	2021	65,000			2
Buffalo	Murrah	Male	Adult	2021	95,000			2
Buffalo	Murrah	Female	Adult	2021	80,000			2
Buffalo	Murrah	Male	Adult	2021	120,000			2
Buffalo	Karnal	Female	Adult	2021	95,000			2
Buffalo	Murrah karnal	Female	Adult	2021	85,000			2
Buffalo	Murrah	Female	Adult	2021	110,000			2
Buffalo	Haryana murrah	Female	Adult	2021	95,000			2
Buffalo	Murrah	Female	Adult	2021	85,000			2
Buffalo	Murrah	Female	Adult	2021	95,000			2
Buffalo	Jafrabadi gir	Female	Adult	2021	130,000			2
Buffalo	Indian	Female	Adult	2021	75,000			2
Buffalo	Murrah	Female	Adult	2021	115,000			2
Buffalo	Girbuffalo	Female	Adult	2021	125,000			2
Buffalo	Murrah	Female	Adult	2021	150,000			2
Buffalo	Murrah	Female	Adult	2021	75,000			2
Buffalo	Graded murrah	Male	Adult	2017	60,000			3
Buffalo	Graded murrah	Female	Adult	2017	65,000			3
Buffalo	Graded murrah	Male	Adult	2017	65,000			3
Buffalo	Graded murrah	Female	Adult	2017	70,000			3
Buffalo	Pure murrah	Male	Adult	2017	70,000			3
Buffalo	Pure murrah	Female	Adult	2017	75,000			3
Buffalo	Pure murrah	Male	Adult	2017	80,000			3
Buffalo	Pure murrah	Female	Adult	2017	85,000			3
Buffalo	Pure murrah	Male	Adult	2017	85,000			3
Buffalo	Pure murrah	Female	Adult	2017	90,000			3
Buffalo	Pure murrah	Male	Adult	2017	100,000			3
Buffalo	Pure murrah	Female	Adult	2017	105,000			3
Buffalo	Pure murrah	Male	Adult	2017	120,000			3
Buffalo	Pure murrah	Female	Adult	2017	130,000			3
Buffalo	Murrah	Female	Adult	2021	75,000	50,000	100,000	8

Table 6 Calf cattle prices

Type	Breed	Gender	Age	Year	Single	Low	High	Website
Cattle	Gir	Male	Calf	2021	71,000			5
Cattle	Gir	Male	Calf	2021	21,000			5
Cattle	Gir	Male	Calf	2021	31,000			5
Cattle	Gir	Male	Calf	2021	51,000			5
Cattle	Gir	Male	Calf	2021	51,000			5
Cattle	Gir	Male	Calf	2021	41,000			5
Cattle	Gir	Male	Calf	2021	65,000			5
Cattle	Gir	Male	Calf	2021	65,000			5
Cattle	Gir	Male	Calf	2021	51,000			5
Cattle	Gir	Male	Calf	2021	60,000			5
Cattle	Gir	Female	Calf	2021	50,000			5
Cattle	Gir	Female	Calf	2021	20,000			5
Cattle	Tharparkar heifer	Female	Calf	2021	25,000			5
Cattle	Kapila	Female	Calf	2021	60,000			5
Cattle	Kapila	Female	Calf	2021	65,000			5
Cattle	Gir	Female	Calf	2021	30,000			5
Cattle	Gir heifer	Female	Calf	2021	10,000			5
Cattle	Black kapila	Female	Calf	2021	60,000			5
Cattle	Gir lildi	Female	Calf	2021	35,000			5
Cattle	Gir lildi	Female	Calf	2021	45,000			5
Cattle	Gir	Female	Calf	2021	20,000			5
Cattle	Gir	Female	Calf	2021	20,000			5
Cattle	Gir	Female	Calf	2021	20,000			5
Cattle	Gir	Female	Calf	2021	20,000			5
Cattle	Gir	Female	Calf	2021	20,000			5
Cattle	Gir	Female	Calf	2021	40,000			5

Table 7 Calf buffalo prices

Type	Breed	Gender	Age	Year	Single	Low	High	Website
Buffalo	Pure murrah	Female	Calf	2021	12,000			5
Buffalo	Murrah		Calf	2021	15,000			5
Buffalo	Murrah	Male	Calf	2021	32,000			5
Buffalo	Murrah	Male	Calf	2021	20,000			5
Buffalo	Murrah		Calf	2021	15,000			5
Buffalo	Murrah		Calf	2021	25,000			5
Buffalo	Murrah	Male	Calf	2021	12,000			5
Buffalo	Murrah	Female	Calf	2021	25,000			5
Buffalo	Murrah		Calf	2021	20,000			5
Buffalo	Murrah	Female	Calf	2021	16,000			5
Buffalo	Murrah	Female	Calf	2021	20,000			5
Buffalo	Murrah	Female	Calf	2021	25,000			5
Buffalo	Murrah	Female	Calf	2021	25,000			5
Buffalo		Female	Calf	2021	57,500	40,000	75,000	6
Buffalo		Female	Calf	2021	12,500	10,000	15,000	7
Buffalo	Pure murrah		Calf	2021	30,000			7
Buffalo	Murrah		Calf	2021	65,000	10,000	120,000	7
Buffalo		Female	Calf	2021	12,500	10,000	15,000	7

Table 8 Price sources for website numbers listed above

No	Website
1	https://www.exportersindia.com/indian-suppliers/pet-animals.htm
2	https://dir.indiamart.com/impcat/buffalo.html
3	http://www.bharathidairyfarm.com/about-murrah.php
4	https://en.engormix.com/MA-dairy-cattle/products/jersey-cows-sale-tamilnadupr32126.htm
5	https://indiancattle.com/search-gowbazaar/
6	https://www.exportersindia.com/search.php?srchcatgty=prod&term=buffalo+calf&cont=IN
7	https://www.tradeindia.com/products/buffalo-calf-c5287276.html
8	http://mahalakshmidairyfarm.in/murrah-buffalo/

Author contribution All authors contributed to the study conception and design. Greg Ferraro led design, analysis, and material preparation. Bret Ericson, Emily Nash, and Andrew Simons contributed to environmental modeling analysis and material preparation. Andrew Simons contributed to economic and livestock outcomes analysis. Mohammed Kabir, Emily Nash, and Bret Ericson lead data collection.

Data availability All data can be made available upon request.

Declarations

Ethical approval This study did not require IRB approval as it did not use human subjects or interventional methods such as surveys. It otherwise followed common ethical standards like anonymity and data security.

Consent to participate This study did not involve participants and therefore did not seek participant consent

Consent for publication All authors have given their consent to publish this work.

Competing interests The authors declare no competing interests.

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