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LETTER

Cadmium: a global assessment of mineral resources, extraction, and indicators of mine toxicity potential

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Supplementary material for this article is available online

Abstract

Mostly produced as a by-product of zinc (Zn) mining, cadmium (Cd) is used in solar photovoltaic cells, battery storage, alloys, pigments, plating, and in nuclear reactors. However, it is also a regulated toxic substance with a long history of environmental and health impacts. As the mining of both Zn and Cd will need to increase to support the global energy transition, the status of Cd as either a resource or a pollutant has major implications for global supply chains and environmental management. Here, we present a new global, site-specific database and analysis of Cd resources in Zn-bearing mineral deposits and mines. Our database, which exceeds past Cd studies in scope, transparency and replicability is made available in full to support future assessments of Cd and Zn resources, mine production and associated risks. It includes 927 sites subject to detailed geological data compilation and analysis. Collectively, these sites suggest a new global resource estimate of 3.3 Mt Cd (95% confidence interval: 2.7–6.1 Mt).

A preliminary geospatial analysis of sites in our database and mine toxicity indicators was also conducted. It shows that:

- A human population of approximately 3.27 million live within 10 km of sites containing Cd resources,
- ∼31% of the world's Cd resources sit within 20 km of International Union for the Conservation of Nature protected areas, and
- Some 28% of Cd mobilised annually by mining originates from areas hosting seasonal or permanent surface water cover.

As ∼27% of Cd resources are in countries that do not refine it, our study highlights the need for further research exploring global Cd trade flows and associated emissions. Heavy metal pollution in mining and metal production regions is an ongoing challenge, and our global dataset refines our understanding of its magnitude and distribution.

1. Introduction

Cadmium (Cd) is a soft, silver-white metal that is often found in small concentrations in zinc (Zn) ores. It was formally discovered by Friedrich Stromeyer in 1817 (Tolcin 2012), although clear records of Cd mining date back as far as CE 710 from the Kamioka mines in Japan (Kean 2011). Commercial production as a by-product of Zn began in the 1860s, with early uses of Cd in rust-proofing supported by the development of a Cd electroplating process around 1919 (Tolcin 2012). It was also used in the production of various alloys, especially for heat-resistant bearings. Cadmium salts were used in art, medicine, and dyeing. By the mid-20th century, uses had expanded to include applications in nickel–cadmium batteries for cars. Although environmental concerns hampered its usage from the 1960s onward (Gauvin 1986), a recent resurgence in usage reflects the integration of Cd in rechargeable nickel–cadmium (Ni–Cd) batteries, and in cadmium telluride (CdTe) photovoltaic (PV) solar cell technology (McNulty and Jowitt 2022). These applications have also established Cd as a metal of interest for the energy transition. Today, Zn-producing, electronics manufacturing countries have become leaders in global Cd production and demand (figure 1, see also figure S7 of the electronic supplementary materials (ESMs)). Forecasts of increasing demand for Cd for solar technologies suggest between a fourfold increase by 2050, to a sevenfold increase by 2040 (International Energy Agency 2022, Collins *et al* 2024), yet due to the toxic effects of Cd on human, plant and animal health (Genchi *et al* 2020), demand outside this sector is slowing.

Environmental exposure pathways for Cd are a major concern (Fatima *et al* 2019), and Zn mining is noted as a key source of Cd contamination globally (Wang *et al* 2021). Several studies have identified serious environmental and health-related risks surrounding Zn-producing mines, smelters and refineries (Paoliello *et al* 2002, Besser *et al* 2009, Sun *et al* 2010, Agnieszka *et al* 2014, Taylor *et al* 2014, Zhou *et al* 2018, Yang *et al* 2018a, 2018b, Wang *et al* 2020, Shi *et al* 2022). Collectively, these studies reveal multiple pathways that Cd can enter the environment, including via:

- **Tailings:** Tailings often contain residual Cd (and other heavy metals) due to the incomplete extraction of metals during ore processing. Tailings stored in ponds or piles can leach Cd into surrounding soils and groundwater, especially if containment systems are poorly managed or fail.
- **Acid Mine Drainage (AMD):** When sulphide ores are exposed to air and water, acidic discharges are formed that are high in dissolved metal concentrations. These can leach (and therefore mobilise Cd) into surface and groundwaters. This is particularly problematic for abandoned mine sites where containment measures are weak.
- **Dust Emissions:** Dust generated during the excavation, crushing, and transportation of zinc ore can be a source of Cd. Any Cd-laden dust resulting from this process can be dispersed by wind and deposited over a wide area, potentially contaminating nearby soils, vegetation, water bodies and even infrastructure (Taylor *et al* 2014).
- **Wastewater:** Water used in the processing of Zn ore can become contaminated with cadmium. This contaminated water may be released into the environment if it is not treated properly before discharge.

With the subsequent uptake of Cd in vegetation, and/or potential for bioaccumulation in aquatic systems, humans can be exposed to cadmium via dust inhalation, ingestion of contaminated water or foods, or direct contact with contaminated soils (Du *et al* 2020). Protocols have been implemented to facilitate a phase-out of cadmium across several uses outside of CdTe PV systems (Sverdrup *et al* 2024), contributing to stagnant rates of by-product recovery relative to Zn throughout the 1900s and into the 200s (figure 2(a)). Reported economic and sub-economic Cd mineral resources in Australia have also declined since 1985, despite significant increases in Zn resources (ESM figure S8).

Despite the prospect of declining Cd demand in future, it is possible that Cd-related pollution may still increase. Cadmium is inevitably extracted and mobilised during Zn mining and smelting, and Zn demand is expected to increase significantly to support an energy transition (Watari *et al* 2020). This raises questions about the extent that the world's Zn-bearing deposits host Cd, and in which locations and mineral systems. However, past studies have yet to produce a clear picture on this.

As shown in table 1, a range of studies have addressed questions of global Cd resources and supply. However, their results vary considerably, using diverse definitions of 'resource'. These studies have also typically relied on average concentrations applied to global volumes, without considering nuances or differences between different deposit types or mines. This leads to a limited understanding of how quantities apportion between countries and locations, and indeed conflicting perspectives on future supply risks. For some, the origin of Cd values used for their estimates are not clear, and as we show in this study, some estimates contradict common geological/geochemical observations. Clear and traceable deposit data are essential to the development of strategies to secure resilient and sustainable Cd supplies, and to manage the ongoing risks and impacts of Zn mining.

The key innovations/outputs of this study are:

(1) The development of a consistent, detailed, and replicable estimate of global Cd resources and their distribution, on a per-deposit basis. We do this through an exhaustive process of identifying mines and mineral deposits hosting Zn–Cd mineralisation and recording or estimating Cd values for each site.
(2) A novel combination of best practice methods in economic geology on database development

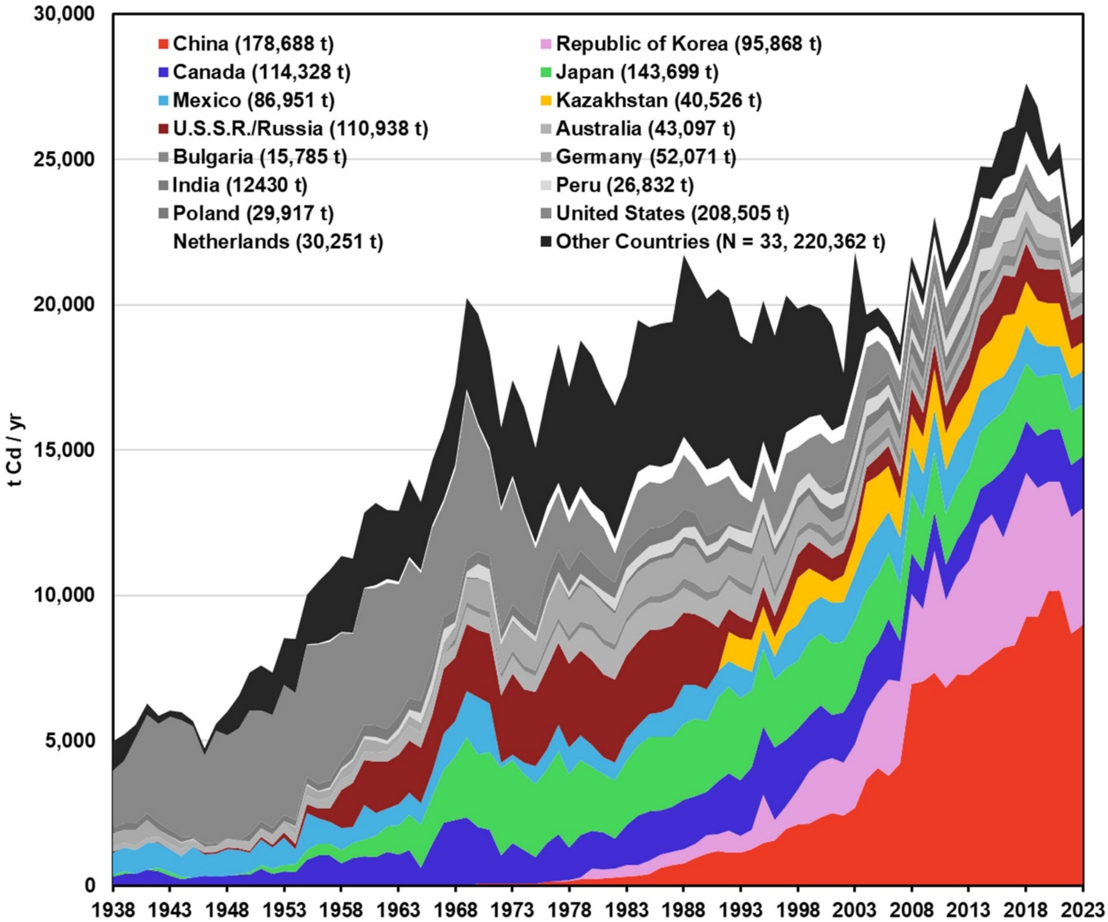

Figure 1. Cadmium production by country (t Cd /yr), 1938–2023. Total cumulative production since 1938 indicated in legend parentheses. Compiled from BGS (Var.) and USGS (Var.). Note that production from the United States dominated throughout the early-mid 20th century, with European production (led by Belgium, France, Italy, Finland and the United Kingdom) notable ca. 1975–2005. The top 7 present day producers (coloured) account for ∼85% of global production.

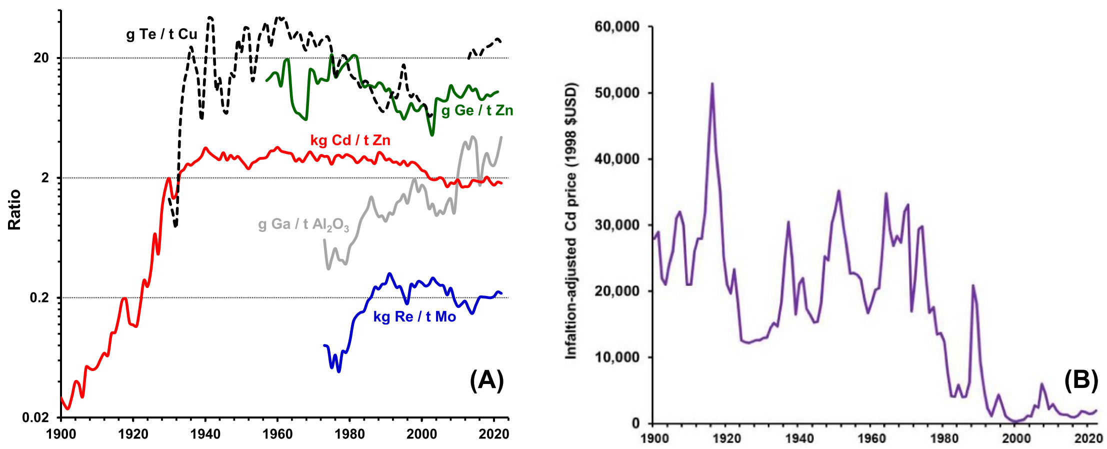

Figure 2. (A) Ratios of companion metals to host production, ca. 1900–2022. Te = tellurium, Cu = copper, Ge = germanium, Ga = gallium, Al_2O_3 = aluminium oxide, Re = rhenium Mo = molybdenum. For Cd, production as a by-product has not increased relative to host production since the 1940s. *Source*: compiled from USGS (Var.), BGS (Var.); (B) Inflation adjusted Cd prices since 1900 (*Source*: USGS, Buckingham *et al* 2024).

and geochemical proxy analysis. We use Monte Carlo simulations to determine Cd grades for each deposit, allowing us to statistically constrain global resource estimates to well within the range shown in table 1.

(3) An analysis of potential toxicity risks emerging from the geographic distribution of Cd in deposits and active mines, as measured by proximity to a set of human/environmental indicators using GIS.

Table 1. Review of past studies and their estimates of global Cd resources.

Source	Estimate	Comments
Arvidsson *et al* (2020)	N/A	No specific resource value given, however the authors rank Cd 13th among 76 elements for 'crustal depletion potential', and 8th for abiotic depletion potential, signalling increased (albeit indirect) risks of resource/supply scarcity, mainly for purposes of conducting life cycle impact analyses.
Mckay *et al* (2009)	0.49 Mt	Geoscience Australia. World Economic Demonstrated Resources (EDR). Also reports 60.8 kt Cd EDR for Australia, and 51.3 Kt Cd JORC Reserves.
Shi *et al* (2019)	0.5 Mt	Described as Cd 'reserves' for 2015, although this classification likely refers to resources/reserves base. Reports Chinese domestic mine production of ∼20–25 kt Cd ca. 2015.
USGS (Var.)	0.57 Mt	Up to 2014, the USGS reported 'reserves' of ∼0.5 Mt. They have since reported that quantitative estimates for Cd reserves and resources are not available. However, they note an average Cd content of 0.03% in zinc ores and report Zn resources of 1.9 billion tonnes in 2023.
Calvo *et al* (2017)	6 Mt	Cites USGS Mineral Commodity Summaries for 2009, although this is a 2017 publication. This study suggests a production peak for Cd ca. 2082.
Karlsson *et al* (2004)	6.791 Mt	Includes 6 Mt in resources, plus 0.791 Mt in reserve base within phosphate rock. Note also that this reference estimates 0.207 Mt Cd in phosphate rock reserves, plus 0.49–0.98 Mt in coal reserves, 0.028 Mt in oil reserves, and 0.57 Mt in Zinc ore (citing the USGS as above), each reported as 'reserves'. As Cd is generally not produced from sources other than Zn ores, it is not correct to interpret these values as 'Cd reserves', but rather, the Cd content of reserves of other commodities. In themselves, they do not present a viable economic source of Cd. These estimates have been produced based on an assumed average concentration range, e.g. 17 ppm in phosphate rock, 0.002–0.1 ppm Cd in oil, 0.5–1 ppm Cd in coal, and 3000 ppm Cd in Zinc ore.
Sverdrup *et al* (2024)	8.158 Mt	Applies average grades and yields/recovery rates to global Zn resource values, based on generic assumptions of the authors. They estimate that global Zn resources contain approx. 20 Mt Cd, of which approx. 8 Mt are extractable. They also estimate it may be possible to produce 250 kt Cd/year. Assumed Cd contents in Pb and Cu ores do not appear geologically sensible, nor are the sources of estimates of global zinc resources clear.
UNEP (2011)	39 Mt	'Extractable global resource (EGR)' reported, based on an assumed proportion of the upper crust. This does not reflect known mines or mineral deposits and represents an upper bound of material contained in the entire upper crust.
Schneider *et al* (2015)	1–100 Mt	A range of potential resource values are reported, also based on crustal abundance. These numbers are not reflective of known mines or mineral deposits and include Cd contents in nonconventional and low-grade materials, plus common rocks. As such, the range shows a high upper bound that includes portions of Cd that are unlikely to be mined in the near future.

In the following sections, we outline our database development and analysis steps, alongside a new summary of global Cd endowments and associated risks. The ESM contains further information on the geological processes underpinning Cd enrichment in (S1), detailed methods and data sources that explain the rigour of the work (S2), spatial analysis results (S3), supplementary figures (S4), a case study on effects as zinc refineries (S5), as well as our full databases (S6, S7).

2. Methods

2.1. Database development and accounting practices

To estimate global Cd resources, we started with an established method for mineral resource accounting and database development explained at length in Werner *et al* (2017a), and which has been applied to indium and rhenium at a global scale in Werner *et al* (2017b, 2023). This method was then modified

Table 2. Overview of collected deposit data.

Type	No. of deposits	Zn in resources (Mt)	Zn capacity (Mt/yr)
All data	927	652.8	12.24
Sulphide deposits	888[a]	360.7[a]	5.00[a]
Non-sulphide deposits	39	26.1	0.54
With Cd data	238 (220 assessable for uncertainty)	294.2	6.70
Cd in sphalerite	214	276.1	6.52
Cd in bulk ore	24	16.0	0.18

[a] Includes tailings storage facilities with available data as separate entities.

to allow for improved incorporation of uncertainties, representing a fusion with uncertainty assessment methods developed by Max Frenzel (Frenzel *et al* 2017, Nassar *et al* 2022, Frenzel 2023). Below, we describe our general approach. Further methodological details and assumptions are outlined in section S2 of the ESM.

Our overall approach consisted of three major components: (1) compilation of a database of reported grades and tonnage of Cd in mineral deposits and other relevant information (e.g. Zn and Pb grades), (2) expanding this database to include deposits likely to contain Cd, but where Cd has not been reported by operating companies, and (3) statistically inferring Cd contents for all unreported deposits, using all available information for each site. Our methods for (3) are significantly more sophisticated than past work as we used a combination of Monte Carlo-type simulations and geochemical proxies. This enabled us to make the best possible use of the available data while at the same time accounting for major sources of uncertainty.

For (1) and (2), we conducted an extensive review of the published literature. This included mining technical reports, industry and government mineral resource atlases and databases, mining company websites, published journal articles and mining industry monographs. For each site, we recorded, where reported: deposit name, resources (ore tonnage), ore grades (Ag, Au, Cu, Pb, Zn), Zn production capacity, location descriptors (province, country, coordinates), operational status, deposit type information (see section S1 of the ESM for further descriptions), as well as all data sources to ensure replicability of the study. Resources contained in tailings storage facilities were also recorded, where suitable data were available. We used the World Directory of Lead and Zinc Mines (ILZSG 2023) to source zinc capacity data for individual mining operations. However, because this is a commercial dataset, the corresponding data column had to be masked in the supplementary materials. Interested readers may purchase the data directly from ILZSG.

Overall, the deposits in our dataset cover 12.2 Mt of annual Zn production capacity (table 2). Given that global zinc production was 12 Mt in 2023 (Tolcin 2024), and that current average capacity utilization is ∼89% for mines around the world (Board Of Governors Of The Federal Reserve System (US) 2024), full capacity is estimated to be around 13.5 Mt. As such, our dataset is likely representative of ∼91% of global Zn production capacity.

It was then necessary to determine what quantities of Cd are likely to exist in each deposit. In some cases, Cd resources are publicly reported, however the quality and transparency of these reports are highly variable. As such, we adopted a reported data classification system described in supplementary section S2.

2.2. Estimating unreported cadmium grades

Using proxy data, we estimated grades of Cd for all deposits where usable information like the deposit type or grades of associated metals were known. As shown in figure 3, Cd grades often positively correlate with Zn and to a lesser degree Pb grades, and so knowledge of other metal grades can be used to infer Cd contents in the ores. However, Cd proxy data vary in their traceability, statistical accuracy and relevance. The types of Cd content/concentration data collected to form the basis of geochemical proxies are described in detail in ESM section S2.2. For each deposit, the geochemical proxies developed considered the logs of Ag, Au, Cu, Pb, and Zn grades. Through the Amelia algorithm, we identified whichever combination of these was available for any one deposit with missing Cd data to constrain a log Cd/Zn ratio, and thus mean Cd content in sphalerite.

Using the proxy data (full datasets provided in ESM sections S6 and S7), we implemented our Cd resource estimates as Monte Carlo-type simulations, since this provides a straightforward method for the propagation of relevant input uncertainties to the overall estimation results (also see Frenzel *et al* 2015, 2016, 2017, Nassar *et al* 2022). Uncertainties assessed in the present case were (1) those related to input data quality for Cd contents in ores and sphalerite, and (2) those related to the absence of Cd data for

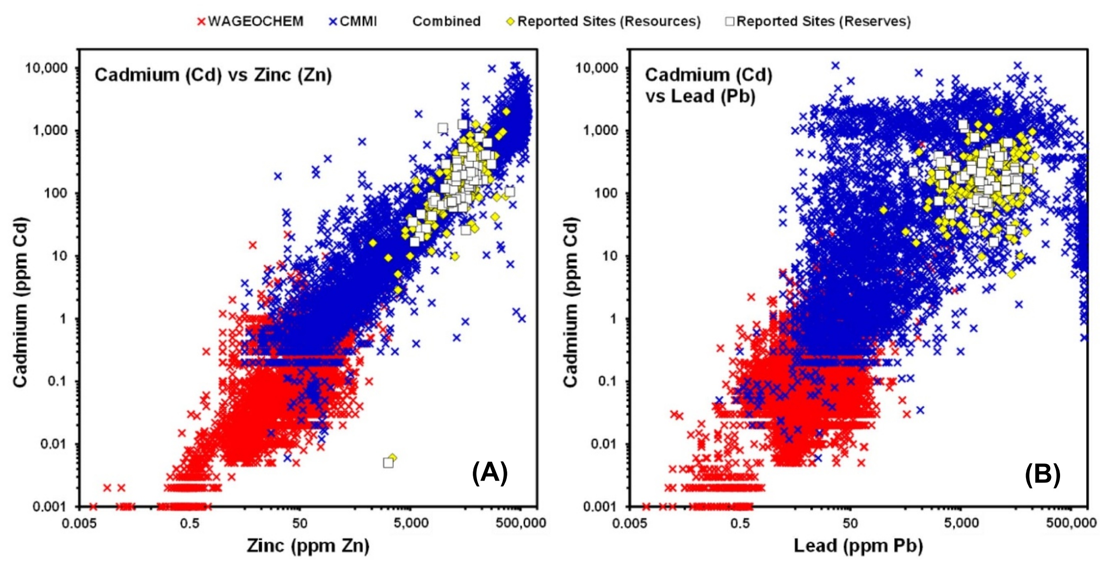

Figure 3. Example of positive correlations between Cd and Zn (A) and Pb (B) grades in samples from our reported database, alongside the Critical Minerals Mapping Initiative (CMMI) and the Western Australia Geochemistry (WACHEM) database. Highlights a general predictive capacity for Cd when commonly reported metal concentrations are known.

Table 3. Spatial data sources used for characterising potential toxicity frontiers.

Source	Name	Details
Hanson (2022), Protected Planet, UNEP-WCMC and IUCN	World Database on Protected Areas	Global database on IUCN terrestrial and marine protected areas. Updated monthly. Polygon data (Vector). Considered for potential to impact areas of significant environmental value.
Buchhorn *et al* (2020)	Copernicus Global Land Cover Layers: CGLS-LC100 Collection 3	Near real time epoch 2019 from the Collection 3 of annual, global 100 m land cover maps. Used Permanent and seasonal water cover layers (Raster) to assess potential water-related impacts.
Schiavina *et al* (2022)	GHS-POP R2023A—Global Human Settlement (GHS) population grid multitemporal (1975–2030)	The spatial raster dataset depicts the distribution of residential population, expressed as the number of people per cell.
Potapov *et al* (2022)	Global maps of cropland extent and change.	Raster, 3 km resolution, 2019 dataset used.

most deposits. Uncertainties on the resource estimates for individual deposits (tonnages, grades) were not included, since these are expected to be comparatively small relative to the uncertainties arising for the Cd values, particularly those missing completely. We approximated the overall amount of Cd hosted in global Zn-bearing base-metal resources, M_{Cd}, by:

$$M_{\mathrm{Cd}} \approx \sum_i T_i \cdot c_i^{\mathrm{ore}}(\mathrm{Zn}) \cdot \frac{c_i^{\mathrm{Sp}}(\mathrm{Cd})}{c_i^{\mathrm{Sp}}(\mathrm{Zn})} \qquad (1)$$

where T_i is the total ore tonnage in deposit i, $c_i^{\mathrm{ore}}(\mathrm{Zn})$ is the average Zn content of the ore in deposit i, $c_i^{\mathrm{Sp}}(\mathrm{Cd})$ is the average Cd content of sphalerite in deposit i, $c_i^{\mathrm{Sp}}(\mathrm{Zn})$ is the average Zn content of sphalerite in deposit i, and the sum runs over all sulfidic Zn-bearing deposits worldwide (this also includes Pb–Zn and Cu–Zn deposits where Zn is not the main commodity of interest). The R software suite (R Core Team 2021) was used for all calculations. Detailed methods for assessing the uncertainties on the Cd input data, imputation of missing values, and data aggregation are outlined in ESM section S2.5.

2.3. Assessing human and environmental hazard potential

While compiling our mineral resource database, we identified the point locations of each of the deposits. Using these points, we used ArcGIS Pro v.2.4.0 software to perform spatial overlay analyses of Cd sites versus human and environmental receptors. We analysed tonnes of Cd in resources, and tonnes Cd contained in zinc production per annum against select categories shown in table 3. These were identified from Ang *et al* (2023), who also provide descriptors. For illustrative purposes, we chose a 10 km buffer zone to represent potential areas directly affected by mining (Junker *et al* 2024), noting that a single coordinate itself may not adequately represent impacts to surrounding regions, and that impacts may extend well beyond this buffer. Further descriptions of the spatial analyses are provided in section S2.6 of the ESM.

3. Results

3.1. Global cadmium resources and flows

Following an extensive review, we identified and classified 238 deposits whose Cd contents could be directly determined from publicly accessible sources. This includes deposits with: (1) reported ore tonnage and Cd grades, (2) reported ore tonnage, Zn grades and Cd concentrations reported in sphalerite, or (3) only reported Cd contents (lacking information on Zn grades or tonnage). These sites are reported to contain a total of 1.4 Mt Cd. Our analysis of the source data underpinning these reports provides a 95% confidence interval of 1.2–2.1 Mt Cd for these deposits. In addition to these sites, a further 689 sites containing Cd-bearing mineralisation were identified, for which proxy estimates were applied.

Figure 4 shows our estimation results for the total Cd contents associated with all global Zn resources and Zn mine production (combining reported + estimated deposits). Our best estimate for the total amount of Cd hosted in global Zn resources is 3.3 Mt, with a 95% confidence interval (CI) of 2.7–6.1 Mt. In addition, our best estimate for the total amount of Cd present within the products of global Zn mine production is 57 kt yr^{-1} (95% CI: 49–121 kt yr^{-1}), or 4.8 kg Cd/t Zn (95% CI: 4.1–10 kg Cd/t Zn). For comparison, global primary Cd production amounted to 23 kt yr^{-1} in 2023 (Callaghan 2024). This reflects that on the order of 35 kt yr^{-1} (26–98 kt yr^{-1}) of Cd are not extracted from zinc concentrates by smelters, and must therefore end up in smelter wastes or emissions. It is beyond the scope of this study to assess pollution/toxicity risks at smelters, however this is clearly an area for further investigation.

3.2. Cd resources and flows by deposit type

Table 4 summarises the results for individual deposit types in our dataset (see supplementary sections S1 and S3 in the ESM for further details on geology and deposit types). This shows that sediment-hosted massive sulphide (SHMS) deposits are clearly the most important host of Cd in Zn resources and in Zn mine production, mostly due to their overall importance as a source of sulphidic Zn ores. Epithermal, high-temperature hydrothermal replacement (HTHR), Mississippi Valley Type (MVT), and volcanogenic massive sulphide (VMS) deposits are essentially of equal median importance as hosts of Cd in resources, even though epithermal deposits host less Zn than the other types, indicating somewhat higher Cd/Zn-ratios in these deposits on average (although this is not significant at the 95% confidence level). Finally, the median contributions of Epithermal, HTHR, and VMS deposits to overall Cd contents in Zn mine production are essentially equivalent, whereas MVT deposits contribute less as a result of the lower production volumes from mining focused on these mineral systems.

Unclassified Zn deposits with reported Cd contents and tailings deposits only have minor contributions to overall global Cd budgets, in line with their comparatively small contributions to Zn resources and Zn mine production. As such their classification is not impactful on the overall assessment of the relative importance of individual mineral systems.

3.3. Cd resources and flows by country

The geographical distribution of reported and estimated Cd resources and production is summarised in figure 5. Figures 6(a) and (b) illustrate uncertainties applicable to resource and extraction estimates for each country. It is clear that despite the level of reporting of Cd resources in each country, there still remains a significant number of deposits for which information is scarce, leading to larger uncertainty bounds for overall Cd contents. Nonetheless, general findings show clearly that countries particularly rich in Zn resources also contain high estimated Cd resources. As shown in figures 5(b) and 6(b), our results also provide a preliminary indication of potential flows of Cd from the lithosphere on an annual basis within each country. Per-deposit estimates are available in the ESM section S6.

3.4. Global cadmium mining toxicity hazard potential

Our spatial overlay analysis of deposits containing Cd reveals some potentially concerning distributions and co-locations. For example, we identified 304 sites containing ~27% of the world's Cd resources that are located within ⩽5 km of the boundary of an International Union for the Conservation of Nature (IUCN)-defined protected area (figure 7, other distributions in ESM section S3.2). This raises concerns for environmental quality in high-value areas. In terms of human health, we found that 412 of the 927 sites (hosting some 47% of global Cd resources) are in areas (⩽10 km radius) with cropland. Among these, 80 sites hosting ~9% of global resources, are in areas with over 20% crop cover (figure 8). In terms of water-related hazards, we estimate that 28% of annually extracted Cd is produced in areas with seasonal and/or permanent water cover within a 10 km distance. These statistics represent only a starting point for further analyses. As shown in figure 8(a), sites with

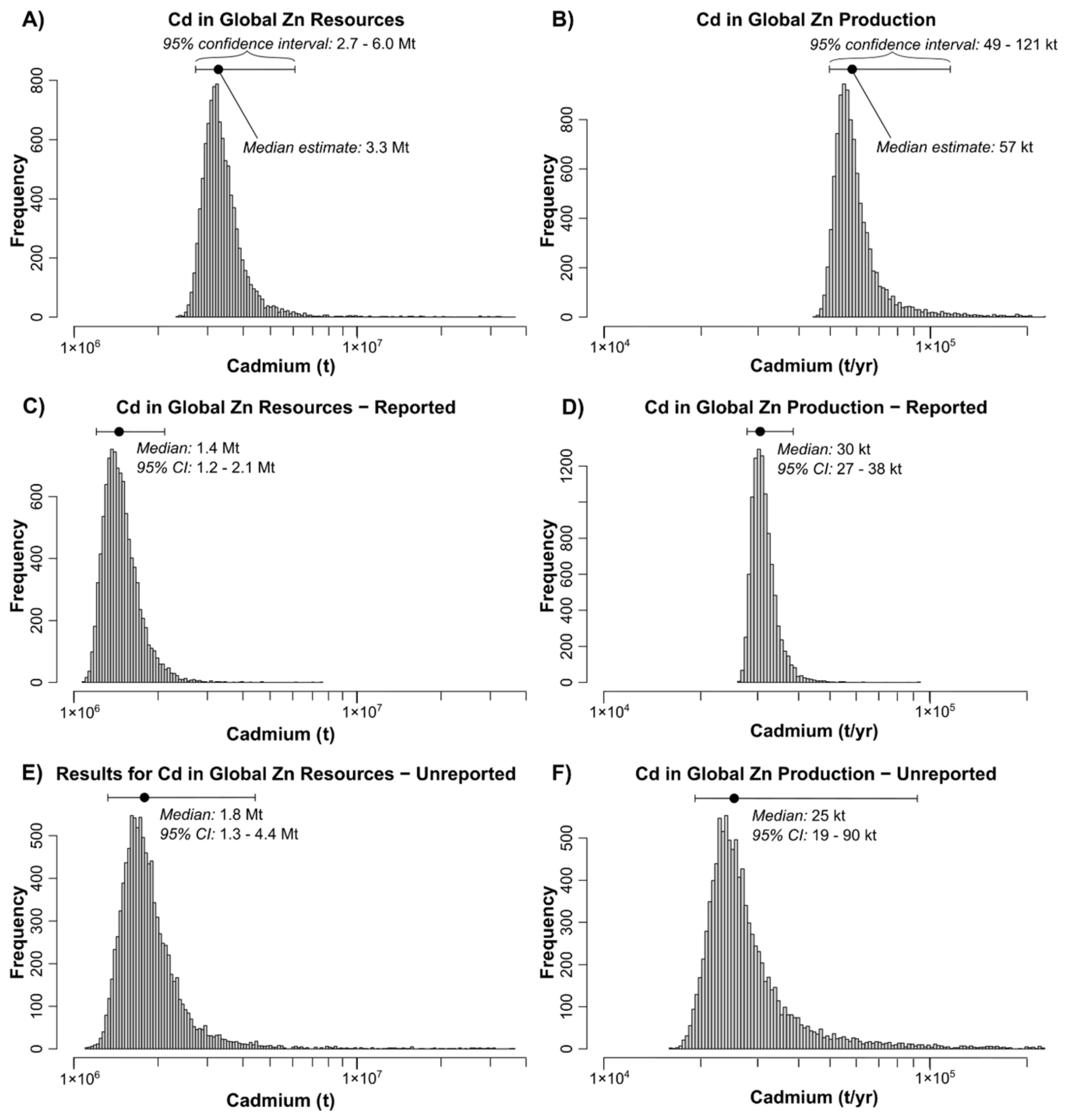

Figure 4. Histograms of estimation results from 10 000 Monte Carlo simulations.

Table 4. Contributions of different deposit types to Cd resources and flows.

Deposit type[a]	Zn in resources (Mt)	Cd in Zn resources (Mt)		Zn production (kt/yr)	Cd in Zn min production (kt/yr)	
		Median	*95% CI*		*Median*	*95% CI*
EPI	57.9	0.49	0.32–2.4	1200	10	6.2–60
HTHR	98.5	0.44	0.35–0.65	2200	9.5	7.9–13
MVT	99.0	0.49	0.31–1.1	970	4.1	2.9–9.5
SHMS	237.9	1.3	0.94–2.1	4100	21	17–30
VMS	113.2	0.41	0.37–0.47	2500	9.2	8.2–11
Other[b]	1.8	0.10	0.08–0.12	51	0.28	0.22–0.36
Tailings	4.1	0.12	0.09–0.25	430	1.2	0.75–3.8

Note: The sum of the medians of the different type subsets is lower than the median of the sum (=global number). This is due to the highly positively skewed distributions of the data and results (cf figure 4).

[a] Deposit characteristics explained in supplementary sections S1 and S2.3.

[b] This only includes those deposits without clear geological deposit type, for which some Cd data was available.

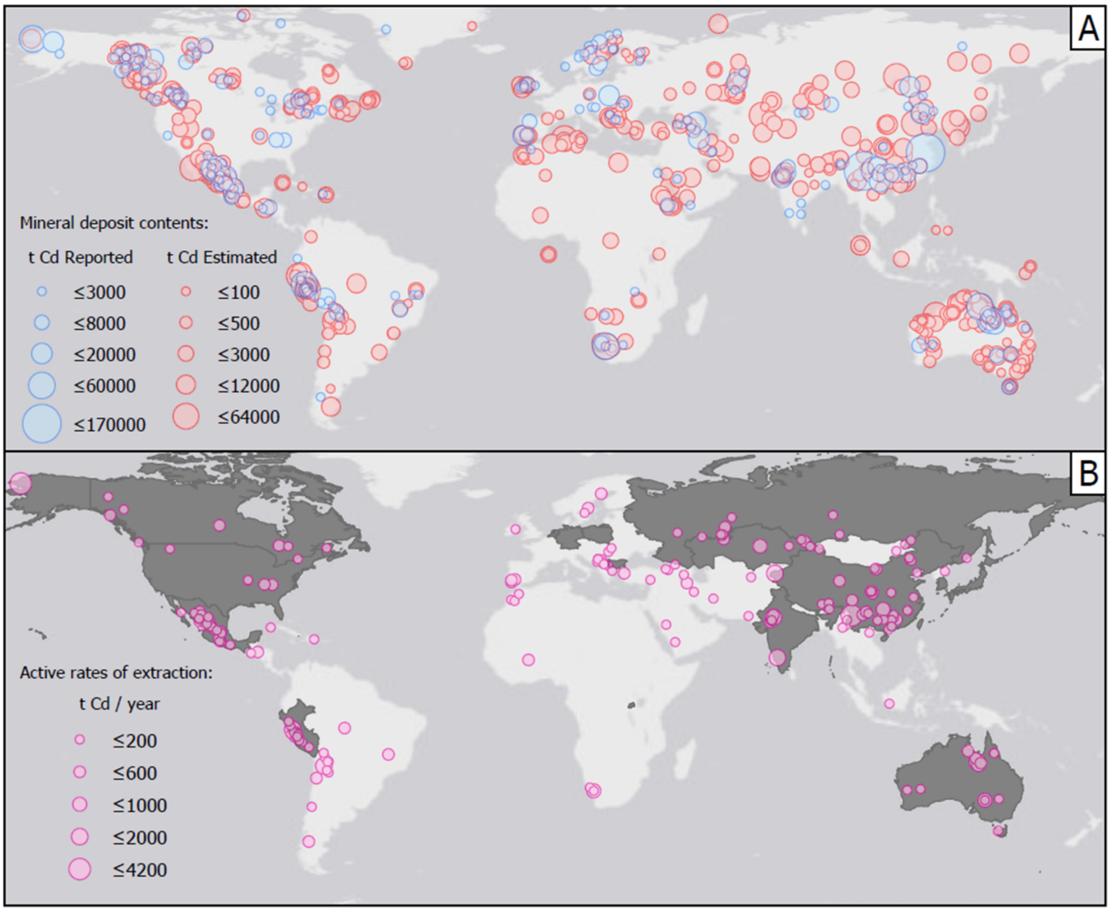

Figure 5. (a) Global map of reported (blue) and estimated (red) Cd contained in mineral deposits (median estimates). (b) Annual rates of Cd extracted due to Zn production (pink, median estimates). Countries darkened in grey are those that currently report refined Cd production per figure 1.

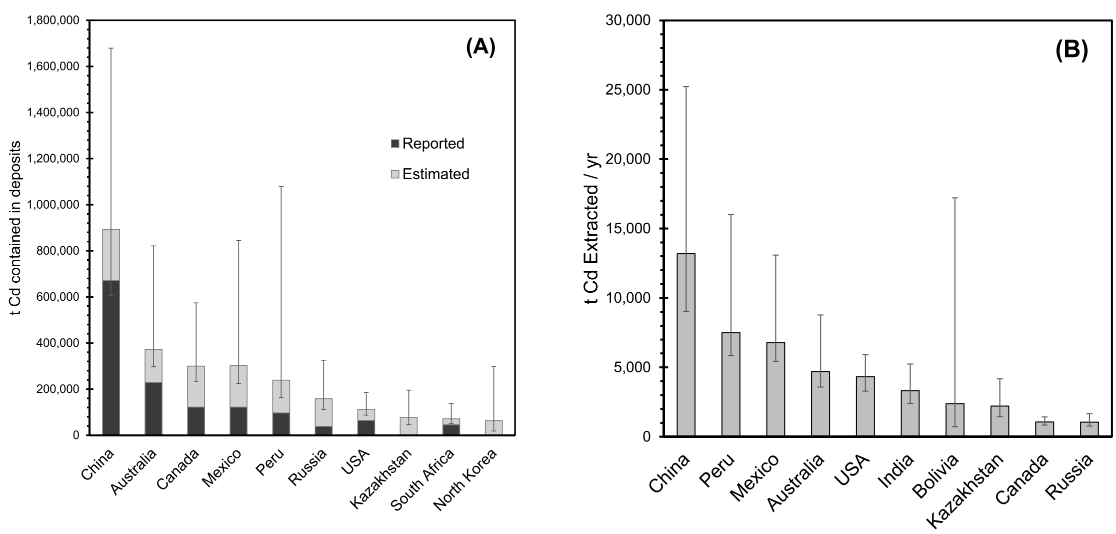

Figure 6. (A): Summary results of median reported + estimated Cd resources per country (top 10). (B): Estimates of annual Cd extracted (i.e. contained in Zn production) per country (top 10). Remaining countries shown in ESM section S4. Error bars indicate 95% confidence intervals arising from Monte Carlo simulations per ESM section S2.5.

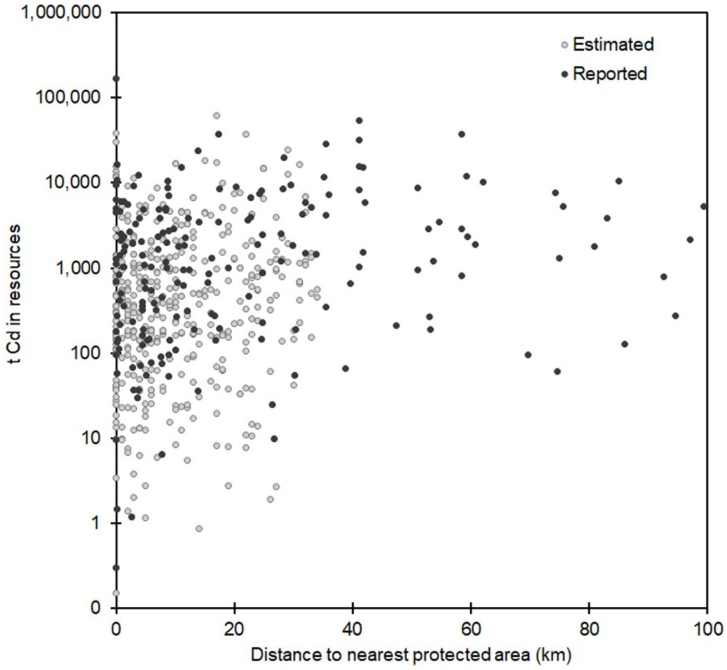

Figure 7. Median estimated resources versus distances to IUCN protected areas per the WDPA (Hanson 2022).

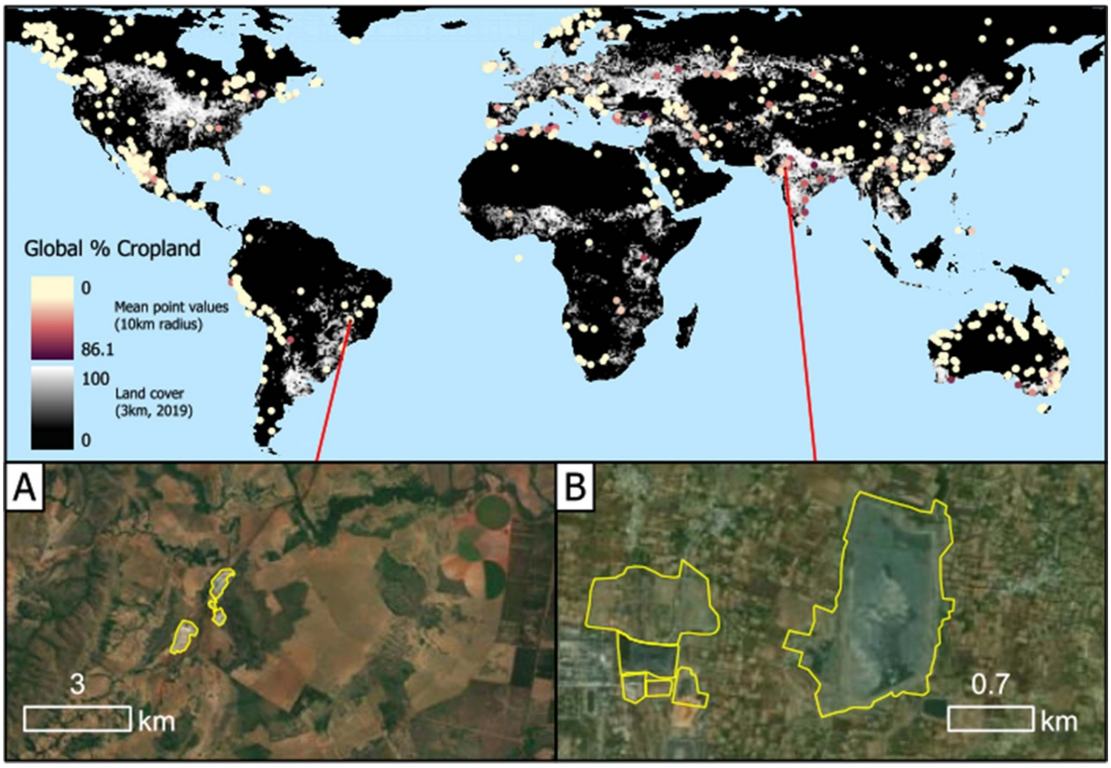

Figure 8. Global % Cropland cover sourced from Potapov *et al* (2022), alongside colour-coded locations of Cd deposits identified in this study. Inset (A): Morro Agudo Mine, Minas Gerais, Brazil, ∼7 kt Cd resources contained, ∼400 t Cd/yr extracted with 6.1% mean cropland cover within a 10 km radius. This is an underground mine operation with decreased landcover footprint, indicating mitigating factors for contamination pathways. However, despite low mean cropland cover, satellite imagery shows close cropland proximity. Inset (B): Rajpura-Dariba Mine, Rajasthan, India, ∼3.7 kt Cd resources, ∼74 t Cd/yr extracted with 43.7% mean cropland cover within a 10 km radius. Mine outlines (yellow) from Tang and Werner (2023). Inset image credits: Esri, Maxar, Earthstar Geographics.

low mean land cover values in surrounding areas can still be situated near to potentially vulnerable features, signalling a need for further site-by-site analyses.

4. Discussion and conclusions

4.1. Resources, demand, and future supply

Past studies have left gaps in our understanding of global Cd deposits and their spatial distribution. This limits our ability to assess the risk and impacts of current and future Cd supply chains. Our study addresses this through the construction of a detailed mineral deposit dataset. Our global resource estimate of ~3.3 Mt Cd highly constrains the vast ranges previously published (<1 up to 100 Mt Cd, table 1) with traceable source data, and includes assessments on a per-site basis.

Quantities of Cd contained in Zn deposits are large, and more than sufficient to support current and predicted rates of production. Current global demand is in the range of 20–25 kt yr^{-1}, or about 2 kg Cd/t Zn (cf figure 4(b)). Comparing this to our estimate of Cd contained in global Zn concentrates (4.8 kg Cd/t Zn; 4.1–9.7 kg Cd/t Zn 95% confidence range), this means ~20%–50% of the contained material is separated during mineral processing. In the past, separation rates have been higher (~3–3.5 kg Cd/Zn t in the 1940s to 1980s). Reported recoveries at smelters in this time are up to 85% (Feiser 1966). As Cd ore grades have not changed significantly in recent decades (see ESM figure S9), the composition of Zn concentrates is likely also to have remained steady. As such, it appears that past smelter recovery rates were simply higher than now (between 30%–85%, assuming same confidence range for past Zn concentrate compositions).

Reduced recovery rates are symptomatic of potential oversupply, given that demand for Zn is high and expected to increase in future. Smelters must still remove Cd from refined zinc products to sell them, and in many jurisdictions, there are strong environmental regulations that require its separation. As such, refined Cd can still make its way to the market despite weak demand signals. This is all strongly reflected in the significant decreases seen in Cd prices over time (figure 2(b)). These patterns of resources, production, recovery and pricing collectively provide confidence that even the most substantial projected increases in long-term demand for Cd in support of energy transition technologies (see (International Energy Agency, IEA 2022), are unlikely to strain supply capacities. Of course, not all elements contained in zinc concentrates may be commercially extractable (cf more detailed discussions on Ga, Ge, In in (Frenzel *et al* 2014, 2015, 2017)). And indeed, other aspects affecting supply and demand, such as the supply of Te for CdTe cells, changes in cell efficiency, and the role of recycling are also important in understanding supply/demand patterns (McNulty and Jowitt 2021, 2022), but they are outside the scope of this study.

Given the multi-layered supply and demand dynamics of Cd, a key function of our deposit database is to highlight where Cd may be present as both a resource and a potential pollutant. Whether it is designated as one or the other (or both) depends heavily on the techno-economic capacities of the mining company operating a site, the supply chains that mine contributes to, and the regulations under which the site operates. As shown in figure 6(a), only a fraction of sites report Cd as a resource. This may be a reflection of Cd being considered a toxic penalty element (and hence not a 'resource'), or that it is simply subject to limited reporting practices, despite having some value (Mudd *et al* 2017, Northey *et al* 2017, McNulty and Jowitt 2021). Given this complexity, it is important to acknowledge that our estimates are uncertain. For simplicity, we have characterised the estimated quantities of Cd situated within the 'resources' of a sphalerite-bearing deposit as 'Cd resources'. However, with the exception of sites where Cd resources are reported via a CRIRSCO code-compliant reporting scheme (see Jowitt *et al* 2020), they more accurately represent 'quantities of Cd within economically extractable volumes of rock'.

4.2. Environmental risks and future work

Given the substantial quantities of Cd available to meet future demands, our results reinforce that Cd toxicity is of far greater concern than its supply security. This is reflected in Cd's absence from many critical minerals lists (DSIR 2024). The continued and expanding mining of Zn will inevitably lead to the mobilisation of Cd. Given that at least 13 other elements are also produced as by-products of Zn, many of which are critical and strategic (Nassar *et al* 2015), the implications of Cd toxicity extend well beyond the supply and demand of Cd alone.

By mapping out mineral deposits and active mines, coupled with data on resources and production flows, our results provide a preliminary, yet more detailed picture of the consequences of Cd supply, and of the mining of Zn deposits in general. Our results highlight several locations of interest. For example, in figure 8, we find that Cd deposits with higher cropland proximity are evident in parts of India. In such croplands, the use of fertilisers with Cd impurities (itself a concern for environmental exposure, (Kubier *et al* 2019) might be exacerbated by mine-related emissions.

Similarly, we note high population proximity for parts of India and China (ESM figure S5), and areas of high overlap with protected zones across many locations globally. One example is the Boleo Mine, Baja California Sur, Mexico, with an estimated ~12 000 t

Cd contained and ∼50 t/yr rate of Cd mobilisation in Zn production, situated within the boundaries of the El Vizcaíno Biosphere Reserve (ESM figure S4). These results can help target ameliorative actions. This might include bioremediation, where heavy metal resistant microbes can be introduced to remove up to 90% of Cd in soils (Kumar *et al* 2021). Conversely, we also identify many regions where very low proximity with risk factors is evident. Such sites might represent more attractive options for responsible sourcing of Cd in future.

Although our results provide a basic measure of potential Cd pollutant loads in a region, they do not reflect management measures taken at each site, do not consider the likelihood of Cd pollutants migrating beyond the immediate vicinity of mining and related operations, and do not incorporate actual concentrations of Cd in soils, flora, fauna, or in human populations in surrounding areas. Our contribution is purely to quantify Cd sources where they have not been quantified, and to geo-locate them at a global scale. Further in-situ work is necessary to examine the ongoing impacts of heavy metal pollution in the locations identified in this study. Given that we have noted the company operating each site, there may be also capacity for future work to consider the extent of foreign direct investment into Cd-containing mines, and further unpack geopolitical supply chain aspects and cross-border management responsibilities (Sun *et al* 2024).

Another key gap in our study is that we do not examine the flows and stocks of Cd at smelters and refineries, which themselves are frequently located close to human populations. It is common practice for smelters to receive Zn concentrates laden with Cd from multiple mines, sourced locally or internationally. This process of converging Cd flows into a smaller number of locations can lead to significant emissions potential at processing facilities, and indeed this is reflected in several case studies (Du *et al* 2020, Wang *et al* 2020). A notable case study is the Risdon Zinc Refinery in Hobart, Tasmania, Australia, whose history we discuss in detail via a case study in ESM section S5.

In Zn smelters, Cd deportment typically includes concentration in (1) the Pb-rich flue dusts generated during roasting of the Zn concentrate, which are processed further at Pb smelters, and (2) the cementation residues generated during cleaning of zinc sulphate solutions prior to electrolysis (Feiser 1966). More work is required to identify the locations and processing capacities of smelters and refineries globally to extend our understanding of the impacts of Zn–Cd (and related by-product) supply chains. Equally, there are numerous sources of Cd emissions beyond the metal mining and production sectors, such as industrial processes, fossil fuel combustion, waste incineration and phosphate fertilisers. We anticipate that our database can be used in conjunction with assessments of these other sources to construct a more comprehensive profile of heavy metal pollution risks globally.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no competing interests.

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