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3. Establishing Soil Heavy Metal Thresholds for Safe and Sustainable Crop Production

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1. Introduction

Heavy metals, defined as metallic elements with a relatively high density (typically greater than 5 g/cm³), are naturally occurring components of the Earth's crust. However, anthropogenic activities such as industrialisation, mining, agriculture (e.g., use of contaminated fertilisers and pesticides), and waste disposal have led to substantial increases in their concentrations in agricultural soils worldwide (Deng *et al*., 2022). Unlike organic pollutants, heavy metals are non-biodegradable and tend to accumulate in the environment, posing long-term risks.

The presence of elevated levels of heavy metals in agricultural soils is a multifaceted environmental problem. Firstly, it directly impacts plant health, leading to reduced growth, yield losses, and compromised crop nutritional quality (Tang *et al*., 2020). Secondly, and more critically, heavy metals can be absorbed by plants and subsequently enter the food chain, posing serious health risks to humans and animals upon consumption (Jaishankar *et al*., 2014). Chronic exposure to even low concentrations of certain heavy metals (e.g., lead, cadmium, arsenic, mercury) can lead to a range of adverse health effects, including neurological damage, kidney dysfunction, cardiovascular diseases, and various cancers.

Given these pervasive threats, establishing robust, scientifically sound soil heavy metal thresholds is imperative to safeguard agricultural productivity, ensure food safety, and promote environmental sustainability. These thresholds serve as critical benchmarks for assessing soil contamination, guiding remediation efforts, and informing policy.

Decisions related to land use and agricultural practices. This article explores the principles, methodologies, and challenges of defining such thresholds, emphasising a holistic approach that integrates ecological, toxicological, and socio-economic considerations.

2. Sources and Pathways of Heavy Metal Contamination in Agricultural Soils

Understanding the origins and movement of heavy metals is fundamental to their effective management. Heavy metals can

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enter agricultural soils through both natural processes and various human activities.

Table 1 Primary Sources of Heavy Metal Contamination in Agricultural Soils

Source	Examples of Heavy Metals	Description
Natural Sources	Cr, Ni, As, Cd, Pb	Weathering of parent rocks, volcanic eruptions, forest fires, and atmospheric deposition of naturally occurring dust.
Anthropogenic Sources		
Industrial Effluents	Cr, Cd, Pb, Hg, Ni, Zn, Cu	Discharge from mining, smelting, electroplating, chemical manufacturing, and textile industries.
Agricultural Inputs	Cd, Pb, As, Cu, Zn	Use of phosphate fertilisers (contaminant Cd), pesticides, herbicides, fungicides (Cu, As), animal manures, and sewage sludge.
Atmospheric Deposition	Pb, Cd, Hg, As	Emissions from fossil fuel combustion, industrial processes, vehicle exhaust, and waste incineration.
Waste Disposal	Pb, Cd, Hg, As, Cr	Landfills, illegal dumping of municipal solid waste, electronic waste, and industrial waste.
Mining Activities	As, Cd, Cu, Pb, Zn, Hg	Tailings, wastewater discharge, and fugitive dust from mining and mineral processing operations.

Once in the soil, heavy metals can undergo various transformations and movements. Their mobility and bioavailability are influenced by several soil properties, including pH, organic matter content, clay content, redox potential, and the presence of complexing ligands (Gupta *et al*., 2020). Low soil pH generally increases the solubility and mobility of many heavy metals, thereby increasing their availability for plant uptake. Conversely, high organic matter content can chelate heavy metals, reducing their bioavailability.

3. Methodologies for Establishing Soil Heavy Metal Thresholds

Establishing soil heavy metal thresholds is a complex scientific endeavour that requires a multidisciplinary approach. Various methodologies have been developed, each with its strengths and limitations.

3.1. Background Concentration Approach

This is often the most straightforward approach, defining thresholds based on naturally occurring heavy metal concentrations in uncontaminated soils within a specific region. It assumes that concentrations exceeding these background

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levels indicate anthropogenic contamination.

- **Advantages:** Relatively simple to determine, provides a baseline for comparison.
- **Limitations:** Natural background levels can vary significantly depending on geology and soil type, making universal application challenging. It does not directly account for ecotoxicological effects.

3.2. Ecotoxicological Risk Assessment (ERA)

ERA is a more sophisticated approach that focuses on the potential adverse effects of heavy metals on soil organisms and ecosystems. It involves comparing measured soil concentrations with ecotoxicological benchmarks derived from laboratory and field studies. Key benchmarks include:

a. **No Observed Effect Concentration (NOEC):** The highest concentration of a heavy metal at which no statistically significant adverse effect is observed on test organisms.
b. **Lowest Observed Effect Concentration (LOEC):** The lowest concentration at which a statistically significant adverse effect is observed.
c. **Predicted No Effect Concentration (PNEC):** A concentration below which adverse effects on the majority of species are unlikely to occur. PNECs are often derived by applying safety factors to acute or chronic toxicity data to account for uncertainties and interspecies variability.

The ERA typically involves several steps:

1. **Hazard Identification:** Identifying the heavy metals of concern and their potential to cause harm.
2. **Exposure Assessment:** Quantifying the actual or potential exposure of receptors (e.g., soil microbes, invertebrates, plants) to heavy metals.
3. **Effect Assessment:** Determining the dose-response relationships for various organisms.
4. **Risk Characterisation:** Integrating exposure and effect assessments to estimate the probability and magnitude of adverse effects.

3.3. Human Health Risk Assessment (HHRA)

HHRA focuses on the potential risks to human health through various exposure pathways, primarily through the consumption of contaminated crops. This approach calculates a soil screening level (SSL) based on acceptable daily intake

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(ADI) or reference dose (RfD) values for specific heavy metals.

- **Advantages:** Directly addresses human health concerns, provides specific limits for food safety.
- **Limitations:** Highly dependent on accurate exposure assumptions, bioavailability data, and reliable toxicological reference values. Does not explicitly consider ecological impacts.

3.4. Bioavailability and Bioaccessibility Considerations

Traditional total heavy metal concentrations in soil do not always accurately reflect the fraction available for plant uptake or absorption by living organisms (the bioavailable fraction). Soil properties influence bioavailability and can significantly alter the actual risk posed by heavy metals.

a. **Bioavailability:** The fraction of a total chemical in environmental media that is available for uptake by organisms.
b. **Bioaccessibility:** The fraction of a chemical that is solubilised from the environmental matrix in the gastrointestinal tract and thus potentially available for absorption.

Incorporating bioavailability into threshold establishment involves using extraction methods that mimic plant uptake or gut digestion (e.g., physiologically based extraction tests, or PBETs). This allows for a more realistic assessment of risk than relying solely on total concentrations.

3.5. Regulatory Frameworks and Guideline Values

Many countries and international organisations have established regulatory limits or guideline values for heavy metals in agricultural soils. These are often blends of the above methodologies that balance ecological protection and human health.

Table 2 Examples of Soil Heavy Metal Guidelines from Different Regions (mg/kg dry weight)

Heavy Metal	EU (Proposed for Sludge)	China (Grade II Soil)	Canada (Agricultural Soil)	Netherlands (Target Value)
Arsenic (As)	15-20	30	12	29
Cadmium (Cd)	1-3	0.3	1.4	0.8
Chromium (Cr)	70-100	250	64	100
Copper (Cu)	50-80	100	63	36

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Lead (Pb)	50-100	100	60	85
Mercury (Hg)	1-2	0.5	6.6	0.3
Nickel (Ni)	30-50	60	50	35
Zinc (Zn)	150-200	200	200	140

Note: These values are illustrative and may vary depending on soil type, land use, and regulatory updates.

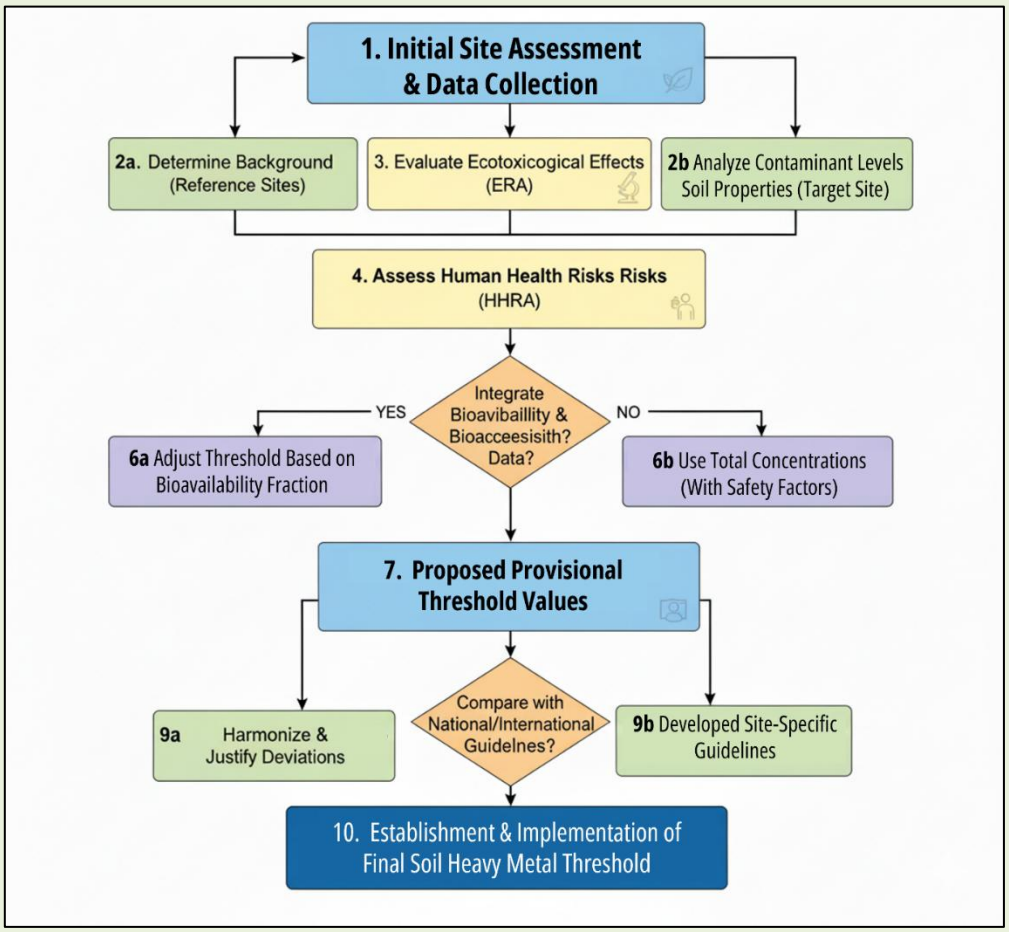

Figure 1 Flowchart for Establishing Soil Heavy Metal Thresholds

4. Challenges and Considerations in Threshold Establishment

4.1. Site-Specific Variability

One of the most significant challenges is the inherent variability of soil properties. Soil type, pH, organic matter content, and clay mineralogy profoundly influence heavy metal speciation, mobility, and bioavailability. A threshold value suitable for sandy, acidic soil may be entirely inappropriate for a clay-rich, alkaline soil. This necessitates a move towards site-specific or regionalised thresholds rather than relying solely on generic values.

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4.2. Multiple Contaminants and Synergistic/Antagonistic Effects

A single heavy metal rarely contaminates agricultural soils. Co-contamination by multiple heavy metals and other pollutants (e.g., organic contaminants) is common. The combined effects of these mixtures can be synergistic (magnified effects), antagonistic (reduced effects), or additive. Current threshold methodologies often struggle to account for these complex interactions, typically assessing metals individually.

4.3. Data Gaps and Uncertainty

Establishing robust thresholds requires extensive ecotoxicological data for a wide range of soil organisms and plant species, under varying environmental conditions. Such comprehensive data are often lacking, particularly for non-model organisms or for chronic exposure scenarios. Uncertainty factors are applied to extrapolate from limited data, but these can introduce significant margins of error.

4.4. Analytical Methodologies

Accurate and consistent analytical methods are crucial for measuring heavy metal concentrations. The choice of extraction method (e.g., total digestion vs. selective sequential extraction) significantly affects measured concentrations and the interpretation of results. Harmonisation of analytical protocols across laboratories is essential for the comparability of data.

4.5. Socio-Economic Factors

The implementation of stringent heavy metal thresholds can have substantial socio-economic implications for farmers, industries, and governments. Remediation of contaminated soils can be extremely costly and technically challenging. Therefore, threshold values often need to balance environmental protection with economic feasibility and agricultural sustainability.

4.6. Dynamic Nature of Soil Ecosystems

Soil is a living ecosystem, with microbial communities playing a vital role in nutrient cycling and in the immobilisation and mobilisation of heavy metals. Heavy metal thresholds should ideally account for the long-term impacts on soil microbial diversity and function, rather than just immediate toxicity to plants or animals.

5. Towards Safe and Sustainable Crop Production

Establishing and implementing effective soil heavy metal thresholds is a critical component of ensuring safe and sustainable crop production. This requires a multi-pronged approach:

a. **Refined Risk Assessment Models:** Development of more sophisticated ecotoxicological and human health risk assessment models that

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incorporate bioavailability, consider mixtures of contaminants, and account for the effects on soil ecosystem services.

b. **Site-Specific Thresholds:** Moving towards the establishment of regional or site-specific thresholds, leveraging local geological data, soil characteristics, and predominant crop types. This can be supported by advanced spatial analysis and GIS technologies.

c. **Advanced Analytical Techniques:** Utilising techniques like speciation analysis (e.g., X-ray absorption spectroscopy, ICP-MS coupled with chromatography) to understand the chemical forms of heavy metals, which dictate their mobility and toxicity.

d. **Early Warning Systems:** Developing monitoring programs and early warning systems to detect rising heavy metal levels before they reach hazardous concentrations.

e. **Sustainable Agricultural Practices:** Promoting practices that minimise heavy metal input (e.g., use of uncontaminated fertilisers, responsible waste management) and enhance the soil's natural capacity to immobilise heavy metals (e.g., increasing organic matter, adjusting pH).

f. **Phytoremediation and Bioremediation:** Investing in research and development of cost-effective phytoremediation (using plants to remove or stabilise contaminants) and bioremediation technologies for already contaminated soils.

g. **Public Awareness and Policy:** Educating farmers, policymakers, and the public about the risks of heavy metal contamination and the importance of adhering to established thresholds and implementing robust regulatory frameworks with precise enforcement mechanisms.

h. **International Collaboration:** Harmonising methodologies and sharing data across international borders to address the global nature of heavy metal pollution.

6. Conclusion

Establishing scientifically sound, pragmatically implementable soil heavy metal thresholds is crucial for addressing the risks posed by heavy metal contamination in agricultural soils. Despite notable advancements in this field, several challenges persist, including variability in contamination across sites, the complexities

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of contaminant mixtures, and the pressing need for extensive ecotoxicological data to inform risk assessments. These factors underscore the importance of adopting a holistic approach that merges advanced analytical techniques with refined risk models and considers the bioavailability of heavy metals. By focusing on these critical areas, we can develop effective thresholds that not only protect agricultural performance but also enhance food safety.

To achieve the goal of sustainable crop production and environmental protection, ongoing collaboration among diverse stakeholders, including scientists, policymakers, industry leaders, and the agricultural community, is imperative. This collective effort will facilitate the continuous refinement of methodologies and the incorporation of new findings into regulatory frameworks. By fostering cooperation and encouraging knowledge sharing, we can ensure that our approaches to managing soil heavy metal levels remain relevant and practical over time. Ultimately, the journey towards establishing clear and enforceable heavy metal thresholds will be a pivotal step in promoting environmental health and securing the well-being of future generations.

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