Long-term efficiency of metal immobilization by soil amendments in a metal contaminated area in Austria

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BACKGROUND AND INTRODUCTION

Non-essential trace metals in soil pose a persistent threat to agricultural productivity and food safety across Europe, particularly in regions affected by historical industrial and mining activities. Due to their non-degradable nature, heavy metals can accumulate in soils over long periods and remain bioavailable, thereby posing risks to crops, ecosystems, and human health.

In the region of Arnoldstein (Carinthia, Austria), centuries of mining and smelting activities (since the 15th century) have resulted in elevated concentrations of Cd, Pb, and Zn in agricultural soils, frequently exceeding national threshold values (ÖNORM L 1075) for safe use:

Values from 2013 vs. 2024:

Cd_{tot}: 7.6 mg kg^{-1} [<1] Zn_{tot}: 1533 mg kg^{-1} [<300] Pb_{tot}: 1252 mg kg^{-1} [<100]

Cd_{tot}: 11,4 mg kg^{-1} [<1] Zn_{tot}: 1432 mg kg^{-1} [<300] Pb_{tot}: 1441 mg kg^{-1} [<100]

Gentle remediation strategies, combining soil amendments with plant-based systems, offer cost-effective approaches to limit transfer into food chain, and enable safe non-food biomass production. This study evaluates the long-term efficiency of gentle remediation – combining soil amendments with vegetation – to immobilize these metals and assess its persistence over a period of 10 years under real field conditions.

EXPERIMENTAL SITE IN ARNOLDSTEIN

Experimental site:



SOIL PROPERTIES

pH_{CaCl2}: 5.8

C_{org}: 42 g kg^{-1}

CEC: 151 mmolc kg^{-1}

P_{CAL}: 4.5 mg kg^{-1}

K_{CAL}: 39 mg kg^{-1}

Cu_{tot}: 86 m g kg^{-1} (100)

SOIL TYPE:
Rendzic Leptosol

TEXTURE CLASS:
SANDY LOAM

Sand: 570 g kg^{-1}

Silt: 250 g kg^{-1}

Clay: 180 g kg^{-1}

EXPERIMENTAL SET UP

Start in spring 2013:

Organic vs. Inorganic amendments

- poplar biochar enriched with nitrogen (P-BCN)
- and/or gravel sludge + iron oxide (GSFe)
- Control: untreated soil

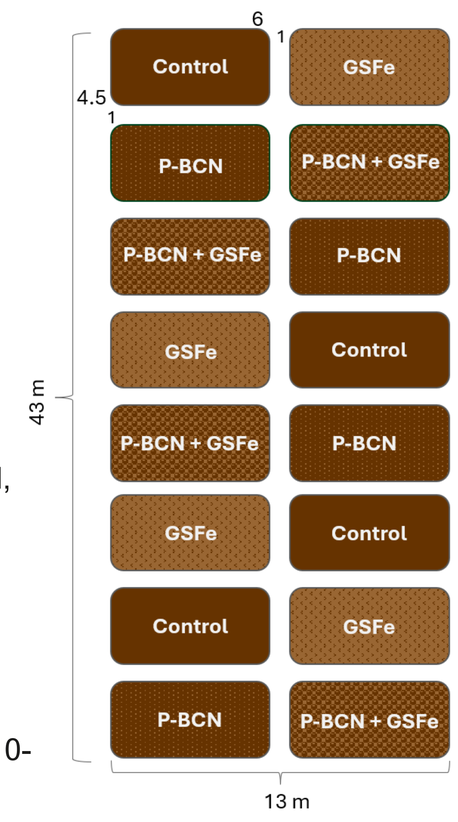
- Application rate of 3% (into 10 cm depth)
- Test plant: *Miscanthus × giganteus*
- 4 treatments × 4 replicates (n = 16)

Assessment in 2014:

- Significant reduction in bioavailability of Zn, Cd, and Pb after amendment application

CURRENT STATUS & CONTINUATION:

- Experiment discontinued at the end of 2014
- Site remained unmanaged until 2024
- Project work resumed in autumn 2024 after a 10-year interruption



ANALYTICAL METHODS

Sampling strategy (2024–2026):

- Biannual sampling (spring & autumn)
- Soil sampled at 0–10 cm and 10–20 cm depths
- *Miscanthus × giganteus* harvested (stems and leaves) from each plot

Soil analysis:

- Bioavailable metal fractions (1 M NH_4NO_3 extract; 1:2.5 w/v) → ICP-MS

Plant analysis:

- Biomass randomly collected per plot, dried, milled, and digested → ICP-MS

Planned additional analyses:

- Soil carbon dynamics (total C, MAOM/POM fractions, stable isotopes)
- Microbial properties (microbial biomass C and N, functional indicators)
- Soil biological activity (e.g. substrate-induced respiration, enzyme activity)

RESULTS

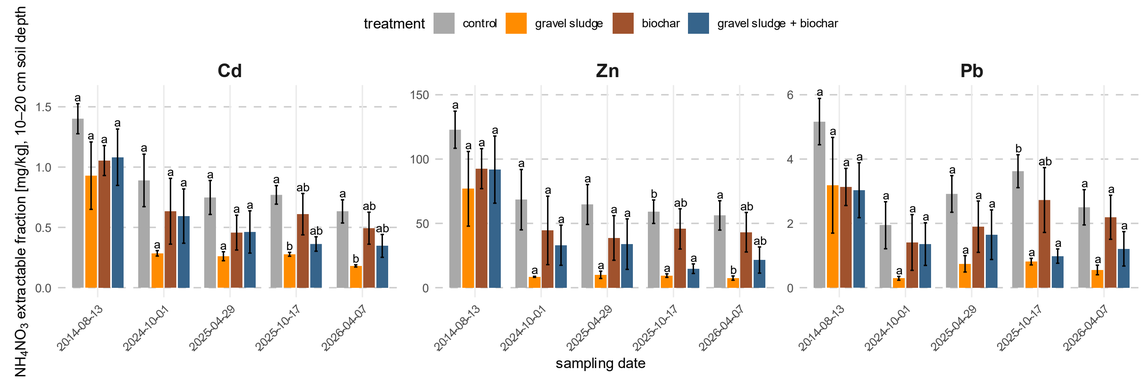
SOIL (BIOAVAILABILITY):

- Application of organic & inorganic amendments significantly reduced bioavailable Cd, Zn, and Pb in the topsoil (0–10 cm) following amendment incorporation in 2013
- Moderate effects were observed in the 10–20 cm layer, where no direct incorporation occurred
- The immobilization effect remained largely stable over time
- Slight remobilization was observed, particularly for Pb

Bioavailable trace metals (NH_4NO_3 extraction, 0–10 cm):



Bioavailable trace metals (NH_4NO_3 extraction, 10–20 cm):

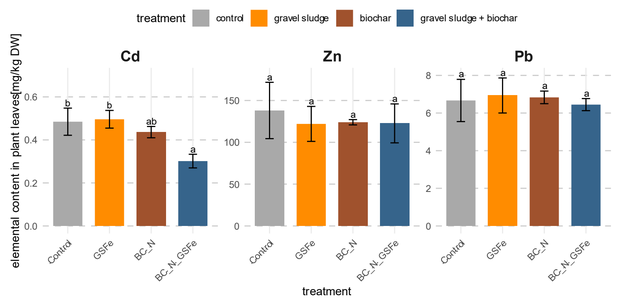


PLANT UPTAKE of *Miscanthus x giganteus*:

Leaves:

- No significant reduction in metal concentrations across most treatments
- Only the combined treatment (biochar + GSFe) showed reduced metal contents

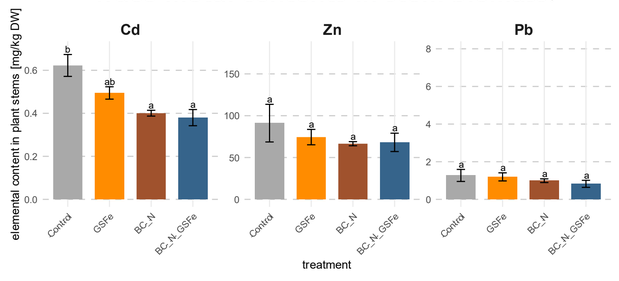
Trace metal contents in leaf biomass:



Stems:

- Significant reduction of Cd concentrations in biochar-treated plots
- Zn and Pb showed moderate, non-significant reductions

Trace metal contents in stem biomass:



CONCLUSION

- Amendments effectively reduced the bioavailability of Cd, Zn, and Pb, particularly in the amended topsoil (0–10 cm)
- Immobilization effect remained largely stable over more than 10 years
- Reductions in plant uptake were limited and element-specific, with significant effects mainly observed for Cd in Miscanthus stems
- The results demonstrate that gentle in situ remediation can provide a long-term reduction in metal mobility while maintaining site usability

👉 This approach represents a promising strategy for safe, non-food use of contaminated soils, supporting sustainable land management in historically polluted regions.

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