# INFLUENCE OF SOIL AMENDMENTS AND TOPOGRAPHIC POSITION ON WINTER WHEAT HEAVY METAL UPTAKE

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## INTRODUCTION

The United States Food and Drug Administration (FDA) recently introduced the Closer to Zero (C2Z) Action Plan which aims to minimize exposure to heavy metals in foods consumed by infants and young children to the lowest levels reasonably achievable. The 2021 Congressional Staff Report prompted this initiative that identified elevated concentrations of arsenic (As), cadmium (Cd), and lead (Pb) in commercially available infant foods. The FDA is expected to establish action levels for heavy metals in "baby and young children's foods," which will likely have significant economic implications for growers and food processors. To ensure a safe food supply, it is essential to understand the factors governing heavy metal uptake by crops within the soil–plant system.

Currently, limited information exists regarding heavy metal uptake by crops grown in Midwestern U.S. agricultural fields. Moreover, there are no established field experiments assessing how soil amendments influence heavy metal uptake nor studies investigating how in-field soil heterogeneity and crop growth stages affect heavy metal accumulation. Although remediation strategies for heavy metals have been extensively evaluated in contaminated environments such as urban soils, research on these issues within conventional agricultural systems remains limited.

In this project, we examined how soil amendments may reduce on-farm heavy metal concentrations in winter wheat (*Triticum aestivum* L.) and assessed the effects of topography and crop growth stages across multiple locations in Michigan.

## MATERIAL AND METHODS

### Study 1: Soil Amendment Strategies

Winter wheat trials were established in Lansing, MI. Among major control mitigation strategies, stabilization was found to be the quickest and most effective method. Treatments were selected in part to test different mitigation mechanisms, including pH adjustment, organic matter complexation, cation substitution, and direct element competition. A randomized complete block design with four replications was established. Treatments investigated included: 1) control, 2) pre-plant agricultural lime (2 T $A^{-1}$), 3) pre-plant dairy compost (5 T $A^{-1}$), 4) pre-plant biochar (2 T $A^{-1}$), 5) pre-plant gypsum (1 T $A^{-1}$), 6) pre-plant granular $ZnSO_4$ (10 lbs. Zn $A^{-1}$) and foliar $ZnSO_4$ (1 pint $A^{-1}$) at Feekes (FK) 9, 7) low N (50 lbs. N $A^{-1}$) at FK 4, 8) moderate N (100 lbs. N $A^{-1}$) at FK 4, 9) high N (150 lbs. N $A^{-1}$) at FK 4, and 10) biodegradable chelating agent ethylenediaminedisuccinic acid (EDDS) sprays with a 2 mmol $L^{-1}$ concentration applied at FK 5, FK 5 + 1 week, and FK 5 + 2 weeks. Autumn starter fertilizer was top-dressed at a rate of 125 lbs. $A^{-1}$ during planting except check. All treatments received a base green-up N application rate of 100 lbs. $A^{-1}$ of urea (46-0-0) except check and N fertilizer treatments.

**Study 2: Field Spatiotemporal Variability (Topography)**

Winter wheat trials were established near Clarksville, MI. Linear transects (six replicates) were established across three slope positions (summit, midslope, and toeslope) resulting in 18 sampling locations per crop year.

**Both Studies**

**Sample Preparation**

Four random soil cores (0-8 in. depth) were sampled from each plot at Feekes 4, Feekes 9, and post-harvest followed by air-drying for 72 hours, ground, and sieved through a 2 mm sieve. Tillers at Feekes 4 and flag leaf at Feekes 9 were washed with tap water to remove soil particles followed by two washes with deionized water. At Feekes 4, tillers were separated into shoots and roots using a Teflon knife after air drying. The shoots were retained while the roots were discarded. Wheat shoots and flag leaves were dried at 158 °F for 72 hours before being ground to 1 mm (UDY Cyclone sample mill). Grain samples were manually cleaned by removing excess husk. Winter wheat grain (50g) was ground into a coarse powder using an electric coffee grinder (Hamilton Beach®, Richmond, VA) for 1 minute.

**Microwave Digestion and Dilution**

Due to variations in microwave digestion protocols, samples were processed in separate batches: (1) soil and (2) plant tissue (i.e., biomass at Feekes 4, flag leaf at Feekes 9, and grains at harvest). Soil samples were digested using a microwave-assisted acid digestion method following EPA Method 3051 (U.S. EPA, 2007) for the acid-extractable fraction. Plant tissue samples were digested at 200 °C with a ramp time of 15 min, a hold time of 15 min, 800 psi pressure, and a power range of 900–1,050 W.

**Elemental Analysis Using ICP-QQQ-MS**

Total cadmium (Cd), arsenic (As), and lead (Pb) concentrations were determined using Triple Quadrupole Inductively Coupled Plasma Mass Spectrometry (ICP-QQQ-MS; 8900 Triple Quadrupole ICP-MS, Agilent Technologies, Santa Clara, CA). Isotopes for each element were selected according to the FDA Elemental Analysis Manual, Section 4.7 ICP-MS Method. Certified reference materials (NIST 1517a tomato leaves and NIST 1515 apple leaves; National Institute of Standards and Technology, Gaithersburg, MD) and at least one analytical blank were included in each run for quality control.

**Plant uptake factor**

The plant uptake factor (PUF) indicates the winter wheat's capacity to absorb a specific element. It was calculated as the plant tissue elemental concentration divided by the soil elemental concentration, where w(plant) is the plant tissue elemental concentration (ppm) and w(soil) is the soil elemental concentration (ppm).

## RESULTS

### Study 1: Soil Amendment Strategies

**Grain yield.** Grain yield ranged from 27.1-127.5 bu. $A^{-1}$ with a mean of 97.2 bu. $A^{-1}$. Low N decreased grain yield ($P$ = 0.0005) by 24.5-25.9 bu. $A^{-1}$ compared to the remaining soil amendments.

**Bulk soil heavy metal concentrations.** The experimental site was established on a Conover loam soil (Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*) with a surface layer of 41.6% sand, 39.2% silt and 19.2% clay (National Cooperative Soil Survey, 2018). Prior to the field experiment, the average concentrations of cadmium (Cd), arsenic (As), and lead (Pb) in the soil were 0.29, 1.4, and 12.7 ppm, respectively. All soil amendments had comparable soil Cd, As, and Pb concentrations across all sampling periods except soil Pb at harvest ($P$ = 0.0369). At FK 4, soil Cd ranged 0.2-0.3 ppm (avg. 0.2 ppm), As ranged 1.8-3.4 ppm (avg. 2.6 ppm) and Pb ranged 9.8-13.2 ppm (avg. 11.0 ppm). At FK 9, soil Cd ranged 0.2-0.3 ppm (avg. 0.2 ppm), As ranged 2.0-3.2 ppm (avg. 2.5 ppm) and Pb ranged 10.2-14.7 ppm (avg. 11.4 ppm). At harvest, soil Cd ranged 0.2-0.3 ppm (avg. 0.2 ppm) and As ranged 1.9-2.9 ppm (avg. 2.5 ppm). EDDS and high N increased soil Pb levels by 0.9 and 0.8 ppm compared to the check. Across sampling periods, the order of soil heavy metal concentration was Pb > As > Cd. Further, heavy metal concentrations were relatively stable across soil amendments and sampling periods (treatment × sampling interaction, $P$ = 0.9997).

**Plant tissue nutrient concentrations.** For both Feekes 4 and 9, Pb was the most prevalent heavy metal followed by Cd and As. However, Cd was the most dominant heavy metal at harvest followed by Pb and As. All soil amendments had comparable plant tissue Cd, As, and Pb concentrations across sampling periods except flag leaf Pb. At FK 4, biomass Cd ranged 0.1-1.3 ppm (avg. 0.3 ppm), As ranged 0.1-0.4 ppm (avg. 0.2 ppm) and Pb ranged 0.3-1.6 ppm (0.6 ppm). At FK 9, flag leaf Cd ranged 0.1-0.3 ppm (avg. 0.2 ppm) and As ranged 0.01-0.02 ppm (avg. 0.01 ppm). High N increased flag leaf Pb level by 0.087 ppm ($P$ = 0.0489) compared to the check. At harvest, grain Cd ranged 0.0-0.2 ppm (avg. 0.1 ppm), As ranged 0.000-0.002 ppm (avg. 0.001 ppm), and Pb ranged 0.00-0.02 ppm (avg. 0.005 ppm). All soil amendments were within the allowable limit set by the FDA (0.01 ppm).

**Plant uptake factor.** All soil amendments had early Cd plant uptake factor (PUF) > 1 with $ZnSO_4$ having the highest Cd PUF (2.06) while both As and Pb PUF < 1 indicated that Cd was readily translocated regardless of soil amendment. Mid-season and harvest Cd, As, and Pb PUF < 1 suggested the reduction of heavy metal uptake efficiency over time.

**Cross-Element Uptake Dynamics Affecting Heavy Metal Accumulation**. Using linear regression, we found that 41% of the variability in grain As uptake may be explained by variation in flag leaf Mg uptake. On the other hand, 25% of the variability in grain Cd uptake may be explained by variation in flag leaf P uptake. While 30% of the variability in grain Pb uptake can be explained by variation in flag leaf Cu uptake.

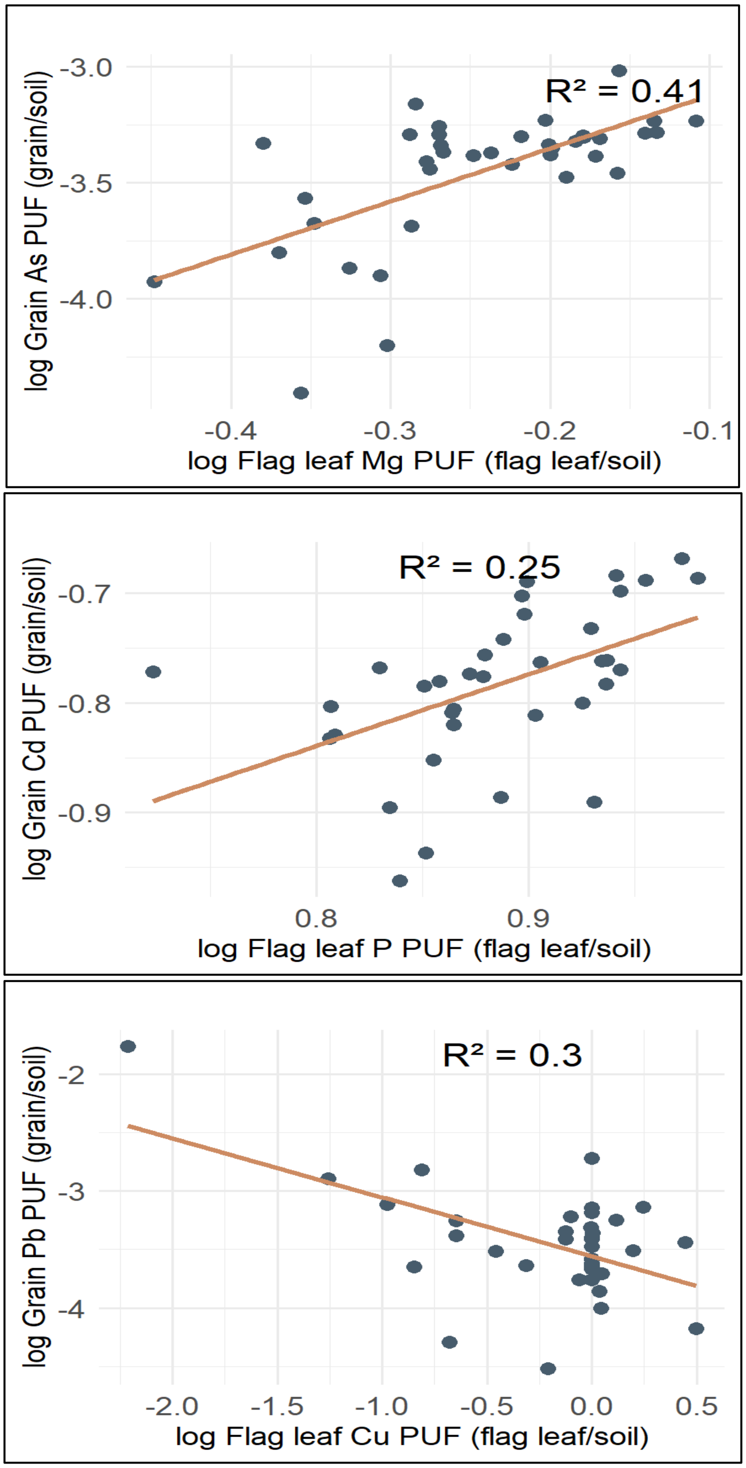


Fig. 1a–c: Linear regression of log flag leaf Mg plant uptake factor (PUF) versus log grain As PUF, log flag leaf P PUF versus log grain Cd PUF, log flag leaf Cu PUF versus grain Pb PUF.

**Study 2: Field Spatiotemporal Variability (Topography)**

**Weather.** As compared to 30-year air temperature and precipitation averages, growing conditions in 2024-25 had normal air temperatures (avg. 21.5-74.1 °F) and a dry autumn (Oct. -84%, Nov. -47%). From December 2024 to March 2025, conditions were warm (+7.5 °F) but contrasting precipitation from Dec. to Feb. (avg. -82%) and Mar. (+33%) precipitation. April to May 2025 had a warm (+8.2 °F) and dry spring (-28%). June 2025 had normal air temperature (avg. 70.4 °F) and dry summer (-37%).

**Soil moisture and 4-day rainfall.** The gravimetric method and 4-day precipitation data were used as contextual indicators of recent soil moisture conditions. At FK 4 ($P$ = 0.416) (12.0-17.5%, avg. 14.7%) and harvest ($P$ = 0.0712) (7.8-12.2%, avg. 9.8%), all slope positions had comparable soil moisture. Conversely, at FK 9 ($P$ = 0.0096), Midslope (14.0%) had the greatest soil moisture, followed by Summit (12.3%) and Toeslope (12.0%).

**Bulk soil heavy metal concentrations.** The experimental site was established on a Lapeer sandy loam (coarse-loamy, mixed, semiactive, mesic *Typic Hapludalf*) with a surface layer of 64.6% sand, 25.6% silt and 9.8% clay and slope 2-6% (National Cooperative Soil Survey, 2018). Across sampling periods, soil As increased over time with lowest at FK 4 (range 1.2-1.8 ppm, avg. 1.4 ppm) and greatest at FK 9 (range 1.4-2.3 ppm, avg. 1.8 ppm), and harvest (range 1.2-2.4 ppm, avg. 1.8 ppm) ($P$ = 5.138e-08). Meanwhile, soil Cd was lowest at FK 9 (range 0.10-0.15 ppm, avg. 0.12 ppm) with lower concentrations at FK 4 (range 0.10-0.15 ppm, avg. 0.13 ppm) and harvest (range 0.10-0.14 ppm, avg. 0.13 ppm) ($P$ = 0.002595). Soil Pb was lowest at harvest (range 5.5-8.7 ppm, avg. 7.4 ppm) and FK 9 (range 6.0-9.1 ppm, avg. 7.5 ppm) and greatest at FK 4 (range 6.5-9.2 ppm, avg. 8.3 ppm) ($P$ = 1.276e-06).

Across slope positions, the order of increasing soil As was Toeslope > Midslope > Summit ($P$ = 2.644e-11); soil Cd was Midslope > Toeslope = Summit ($P$ = 3.349e-09); and soil Pb was Toeslope = Midslope > Summit ($P$ = 4.887e-13). The decreased acid-extractable heavy metal concentrations likely indicate that winter wheat absorbs higher levels, while greater values suggest that the crop takes up less.

**Plant tissue nutrient concentrations.** For both Feekes 4 and 9, Pb was the most prevalent heavy metal followed by Cd and As. On the other hand, Cd was the most dominant heavy metal at harvest followed by Pb and As. All slope positions had comparable plant tissue Pb across sampling periods. Biomass Pb ranged 0.3-1.0 ppm (avg. 0.6 ppm), flag leaf Pb ranged 0.01-0.2 ppm (avg. 0.1 ppm) and grain Pb ranged 0.0-0.01 (avg. 0.001 ppm). Grain Pb was within the allowable limit set by the FDA (0.01 ppm). Plant tissue As was consistently greatest in Toeslope with 0.3, 0.01, and 0.002 ppm during FK 4 ($P$ = 0.0272), FK 9 ($P$ = 0.0179) and harvest ($P$ = 0.013), respectively. Slope positions influenced flag leaf Cd ($P$ = 0.0053) and grain Cd ($P$ = 0.0067) with Midslope having greatest flag leaf Cd (0.16 ppm) and Midslope (0.05 ppm) and Summit (0.05 ppm) having the greatest grain Cd levels.

**Plant uptake factor.** All slope positions had early Cd plant uptake factor (PUF) > 1 with Summit having the highest Cd PUF (2.71) while both As and Pb PUF < 1. Midslope and Summit had both mid-season Cd PUF > 1.0 while both As and Pb PUF < 1.0. Late-season As, Cd, and Pb PUF <1.0 however Summit remained having the greatest Cd PUF among Midslope and Toeslope.

## Cross-Element Uptake Dynamics Affecting Heavy Metal Accumulation

Using linear regression, we found that 20% of the variability in grain As uptake could be explained by variation in flag leaf Mn uptake. In contrast, 69% of the variability in grain Cd uptake could be explained by variation in flag leaf K uptake, while 33% could be explained by variation in flag leaf Zn uptake. None of the elements significantly influenced grain Pb uptake in either the FK 4 or FK 9 sampling (V, Cr, Mn, Co, Ni, Cu, Zn, As, Se, Cd, Pb, Al, Ca, Fe, K, Mg, Na, P, S).

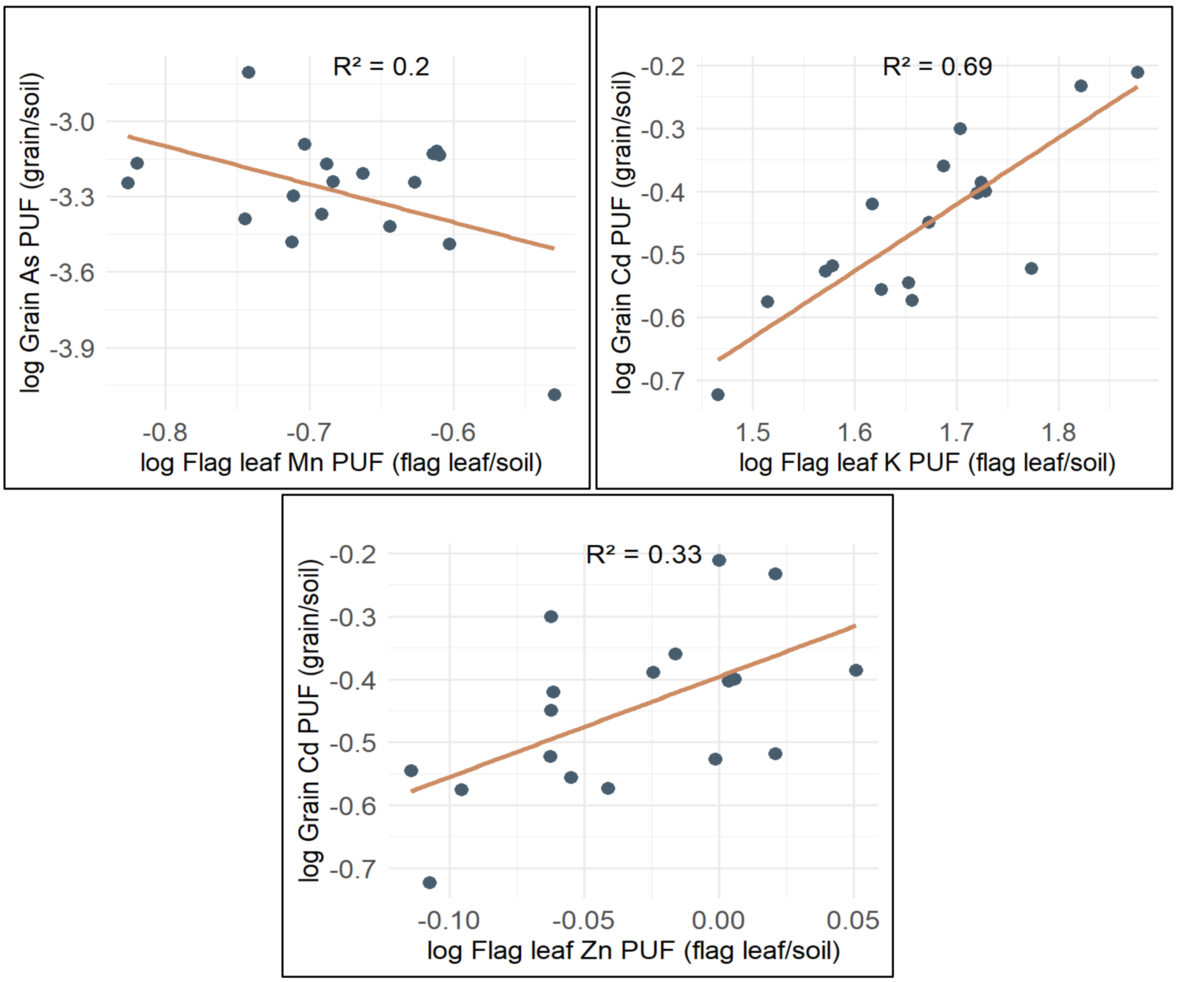


Fig. 2a–B: Linear regression of log flag leaf Mn plant uptake factor (PUF) versus log grain As PUF and log flag leaf K PUF, flag leaf Zn PUF versus log grain Cd PUF.