

Vertical Distribution Characteristics of Cadmium in Long-term Sewage-Irrigated Soil After Single Sewage Irrigation: Postprint

Authors: Xin Lujun, Qi Xuebin, Guo Jianqing, Fan Xiangyang, Liu Yan, Hu Yanling

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Abstract

Taking a ~328 m² field in the Niangniangmiao wastewater irrigation area of Xinxiang City, Henan Province as the study area, this study employed a combination of methods including mean, coefficient of variation, semivariogram, and fractal dimension to analyze the vertical spatial variation and distribution characteristics of soil available cadmium in east-west profiles A, B, C, and D (with one profile established every 10.5 m in the north-south direction, numbered A, B, C, and D from north to south) within 10 days before and after a single wastewater irrigation event, providing a fundamental exploration for the research approach combining available cadmium distribution in field soils with soil phytoremediation. The results showed that after irrigation, the mean soil available cadmium content in profiles A, B, C, and D decreased by 0.06 mg kg⁻¹, 0.11 mg kg⁻¹, 0.14 mg kg⁻¹, and 0.23 mg kg⁻¹, respectively, exhibiting a moderate degree of dispersion; within the range of 0.393~1.308 m, the nugget-to-sill ratio $C/(C+C)$ was <25%, indicating that the overall variation in soil available cadmium profiles caused by random factors was relatively small and spatial correlation was strong; the fractal dimension of soil available cadmium in profiles A, C, and D decreased, and the degree of spatial variation weakened. Kriging interpolation results indicated that available cadmium in the study area exhibited a banded distribution pattern, with accumulation observed in the 0~15 cm soil layer; along the irrigation direction, the distribution of contour lines for soil available cadmium content in the profiles changed from dense to sparse. Correlation analysis revealed that soil available cadmium content was positively correlated with soil organic matter content, moderately correlated with soil water content, and strongly negatively correlated with pH, manifesting as higher soil organic matter content corresponding to greater soil available cadmium content, and higher pH corresponding to lower soil available cadmium content; wastewater irrigation had significant effects on soil available cadmium, soil water content,

soil pH, and soil organic matter, while simultaneously weakening the correlations between available cadmium and each influencing factor. The distribution and variation characteristics of available cadmium associated with wastewater irrigation dynamics can provide fundamental data for research on soil heavy metal pollution remediation using plant adsorption.

Full Text

Vertical Variability of Cadmium After One Sewage Irrigation in Long-Term Sewage-Irrigated Areas

XIN Lujun¹, QI Xuebin¹, GUO Jianqing², FAN Xiangyang¹, LIU Yan¹, HU Yanling¹

(1. Institute of Farmland Irrigation Research, Chinese Academy of Agricultural Sciences, Xinxiang 453003, China;

2. Institute of Environmental Sciences and Engineering, Chang' an University, Xi' an 710054, China)

Abstract

This study investigated the vertical spatial variability and distribution characteristics of available cadmium in soil profiles following a single sewage irrigation event in a 328 m² field located in the Niangniangmiao sewage irrigation area of Xinxiang, Henan Province. Four east-west oriented profiles (A, B, C, and D) were established at 10.5 m intervals along a north-south transect. Using classical statistics, geostatistics, and fractal analysis, we analyzed changes in soil available cadmium over a 10-day period before and after irrigation. Results showed that after irrigation, mean available cadmium concentrations decreased by 0.06, 0.11, 0.14, and 0.23 mg · kg⁻¹ in profiles A, B, C, and D, respectively, exhibiting moderate dispersion. Within a range of 0.393–1.308 m, the nugget-to-sill ratio [$C/(C+C)$] was less than 25%, indicating that random factors contributed minimally to overall variation and that strong spatial correlation existed. Fractal dimensions decreased in profiles A, C, and D, suggesting weakened spatial variability. Kriging interpolation revealed a banded distribution pattern of available cadmium, with accumulation occurring in the 0–15 cm soil layer. Contour lines became less dense along the irrigation direction from south to north. Correlation analysis demonstrated positive relationships between available cadmium and soil organic matter, moderate correlation with soil moisture, and strong negative correlation with pH. Sewage irrigation significantly affected soil available cadmium, moisture, pH, and organic matter while weakening correlations between cadmium and these influencing factors. These findings on the dynamic distribution and variability of available cadmium provide baseline data for research on phytoremediation of heavy metal-contaminated soils.

Keywords: Sewage irrigation; Soil profile; Available cadmium; Spatial variability; Heavy metal

Introduction

Soil properties exhibit inherent spatial heterogeneity, which imparts distinct spatial distribution patterns to heavy metals in soils. Since Matheron systematized the concept of “regionalized variables” in the 1960s and McBratney et al. developed geostatistical theory in the 1980s, the quantitative study of soil spatial variability has advanced considerably. These methods have been successfully applied to investigate spatial distributions of soil moisture characteristics, water-salt dynamics, soil nutrients, heavy metals, and other elements through integrated applications of GIS and Kriging interpolation.

In northern China, uneven water resource distribution has led to a long history of sewage irrigation for agriculture, resulting in varying degrees of soil contamination that constrain agricultural economic development in these areas. Heavy metals represent primary pollutants from sewage irrigation, with affected areas continuously expanding, particularly cadmium and mercury contamination. Soil heavy metals exhibit distinct spatial correlation within certain ranges, and spatial estimation can effectively characterize their variability at different scales within the same region. However, most existing research has focused on large-scale or multi-scale assessments of heavy metal pollution in surface soils of irrigated areas, with fewer studies examining vertical distribution patterns. Previous vertical distribution research has primarily concentrated on heavy metal leaching and migration characteristics. Long-term irrigation studies show heavy metals accumulate in surface soils, with cadmium leaching more readily than lead. Therefore, further investigation of small-scale vertical profile spatial variability of soil heavy metals in irrigation districts is necessary.

This study selected a long-term sewage-irrigated field in Xinxiang, Henan Province, to examine spatial variability and distribution characteristics of available cadmium before and after irrigation using classical statistics, geostatistics, Kriging interpolation, fractal theory, and correlation analysis. The results provide fundamental insights for integrating available cadmium distribution with soil-plant remediation strategies.

1.1 Study Area Description

Xinxiang City is located in northern Henan Province along the middle and lower reaches of the Yellow River, serving as a major political, economic, cultural, and transportation center in northern Henan and an important battery production base. The study field is situated in the Niangniangmiao irrigation district on the city's outskirts, where winter wheat-summer maize rotation has been practiced extensively for years using water diverted from the Wei River. The Wei River flows from west to east through the irrigation district with an average annual flow of approximately $2 \text{ m}^3 \cdot \text{s}^{-1}$. Due to long-term acceptance of irrigation return flow and municipal wastewater, the Wei River has become an ecologically

degraded drainage channel. Despite deteriorating water quality, the irrigation district continues using it as a primary water source to alleviate agricultural water scarcity. The study area soils are primarily silty clay. Irrigation water analysis revealed that total nitrogen exceeded standards for dryland irrigation (GB 5084-2005), while COD_{Cr} and total nitrogen exceeded Class V surface water environmental quality standards (GB 3838-2002).

1.2.1 Sample Collection

The study plot measured 42 m (north-south) by 7.2 m (east-west). To manage sampling and laboratory workload, four profiles were established at 10.5 m intervals along the north-south axis, designated A, B, C, and D from north to south, with end profiles positioned 5.25 m from field boundaries. Along each profile, sampling points were spaced at 0.9 m intervals, yielding seven points per profile with end points 0.9 m from field edges. Based on background soil values prior to wheat planting and the slow migration of heavy metal ions with minimal distribution changes, soil samples were collected using a 5 cm diameter auger to a depth of 1 m at 10 cm intervals. This created a rectangular grid of 28 sampling points per profile for measuring soil moisture content, pH, organic matter, and available cadmium before and after irrigation.

Irrigation occurred on April 25, 2013, with sampling conducted on April 15 and May 2, 2013; no precipitation occurred during the interval. The irrigation volume was approximately 60 m³ per event, applied as flood irrigation (infiltration depth 40–60 cm) moving from south to north perpendicular to the profile orientation. Initial characterization involved five S-shaped sampling locations across the field, with three boreholes per location sampled to 80 cm depth at 10 cm intervals. Composite samples were analyzed, yielding baseline soil properties: total cadmium 1.02 mg · kg⁻¹, available cadmium 0.356 mg · kg⁻¹, pH 8.5, organic matter 2.14%, bulk density 1.42 g · cm⁻³, with silty clay texture throughout 0–40 cm. Wei River water characteristics were: pH 7.38, electrical conductivity 2913.33 S · cm⁻¹, COD_{Cr} 72.77 mg · L⁻¹, total nitrogen 23.17 mg · L⁻¹, total potassium 12.87 mg · L⁻¹, cadmium 0.004969 mg · L⁻¹, lead 0.001402 mg · L⁻¹, and chromium 0.002107 mg · L⁻¹.

1.2.2 Sample Analysis

During collection, each auger core was divided: one portion was placed in aluminum boxes, oven-dried at 105°C for 12 hours, and weighed to determine moisture content; the other portion was sealed in plastic bags, air-dried in the laboratory, ground, and passed through a 2 mm nylon sieve. Available cadmium was extracted using DTPA (diethylenetriaminepentaacetic acid) at a 1:2 soil-to-solution ratio, shaken for 2 hours, and filtered. Concentrations were measured using a Shimadzu AA-6300 atomic absorption spectrophotometer. Organic matter was determined by low-temperature external heating potassium dichromate oxidation-colorimetry, with absorbance measured using a Shanghai Jingke 752N UV-Vis spectrophotometer. Soil pH was measured potentiometrically in a 1:5

soil-to-water suspension using a Shanghai Jingke PHS-3E pH meter. All methods followed *Soil Agricultural Chemical Analysis Methods*. Laboratory analyses were conducted at the Key Laboratory of Water Resources Safety and Efficient Utilization, Chinese Academy of Agricultural Sciences.

1.2.3 Data Processing

SPSS software was used for statistical parameter calculation, normality testing, and correlation analysis. Geostatistical analysis software GS+9.0 fitted semivariogram models and calculated fractal dimensions. SURFER software performed Kriging interpolation to generate contour maps. Computational principles followed established literature.

2.1 Statistical Analysis of Soil Properties and Available Cadmium

Mean values and coefficients of variation for soil available cadmium, moisture content, pH, and organic matter are presented in Table 1. F-test results from ANOVA showed all P-values were 0 except for profile A available cadmium ($P=0.04$), with all profile P-values <0.05 , indicating sewage irrigation significantly affected the distribution of available cadmium, moisture, pH, and organic matter.

After irrigation, mean available cadmium in profiles A, B, C, and D decreased by 0.06, 0.11, 0.14, and 0.23 $\text{mg} \cdot \text{kg}^{-1}$, respectively, showing moderate dispersion. Pre-irrigation coefficients of variation were similar across profiles (39.29%–45.53%). Post-irrigation values remained moderately dispersed, with variation decreasing by 9.39%, 4.32%, 6.12%, and 10.98% in profiles A, B, C, and D, respectively (range: 28.31%–45.16%). These results indicate that vertical profile variability of available cadmium tended to decrease after irrigation, with redistribution and homogenization occurring through migration and transformation processes.

Moisture content means changed by -4.89%, 4.20%, 5.21%, and 6.05% in profiles A, B, C, and D, respectively. Except for profile A, moisture increased in all profiles. The decreased moisture in northern profile A likely resulted from the south-to-north irrigation method, which caused shallower infiltration and greater evaporation in the northern section. Pre-irrigation moisture showed moderate dispersion in profile B and similar variation in others (6.02%–7.12%). Post-irrigation moisture exhibited weak dispersion, with variation decreasing by 28.01% in profile B and 4.49%, 4.49%, and 1.60% in profiles A, C, and D, respectively (range: 1.53%–4.96%), indicating weakened vertical variability in moisture after irrigation.

Mean pH values decreased slightly in all profiles, showing irrigation caused minor pH changes. Both pre- and post-irrigation pH exhibited weak dispersion, with variation changing by +0.02% in profile A and decreasing by 0.20%, 0.07%,

and 1.19% in profiles B, C, and D, respectively, indicating reduced vertical pH variability after irrigation.

Organic matter means increased by 7.1, 5.7, 3.5, and 2.2 $\text{g} \cdot \text{kg}^{-1}$ in profiles A, B, C, and D, respectively. Variation decreased by 2.43%, 5.58%, and 2.28% in profiles A, B, and D, while increasing 1.14% in profile C, showing moderate dispersion overall. The increased organic matter content with reduced variability suggests that enhanced soil aggregate structure following irrigation decreased dispersion.

Overall, traditional statistical analysis revealed that sewage irrigation tended to reduce the dispersion of soil available cadmium, moisture content, pH, and organic matter.

2.2 Spatial Variability Characteristics of Soil Available Cadmium

Geostatistical theory uses the nugget value (C) and nugget-to-sill ratio [$C/(C+C)$] to characterize the degree of random variation and spatial correlation strength, respectively. Semivariogram modeling parameters from GS+9.0 are presented in Table 2.

Nugget values differed substantially before and after irrigation. Profile A showed a marked increase, while profiles B, C, and D decreased by 98.6%, 52.7%, and 86.2%, respectively (range: 1.0×10^{-7} – 7.8×10^{-3}). This indicates random factors dominated spatial variability in profile A, while overall vertical variability showed minimal influence from anthropogenic activities such as fertilization, tillage, and cropping systems.

Post-irrigation $C/(C+C)$ ratios ranged from 0.002 to 0.238. Compared with pre-irrigation values, ratios increased in profiles A and C (indicating random-dominated variation) but decreased substantially in profiles B and D (indicating weakened random effects). Overall, sewage irrigation resulted in small random-induced variation and strong spatial correlation of available cadmium in vertical profiles.

The range values indicated post-irrigation spatial autocorrelation extended 0.393–1.308 m. Profile B showed a reduced autocorrelation range compared with expanded ranges in profiles A, C, and D. The range represents the distance beyond which observations become spatially independent, suggesting profile B's correlation zone contracted. Across the experimental field, available cadmium exhibited an overall trend of expanded spatial correlation ranges, representing weak variation at small scales.

2.3 Fractal Dimension Analysis of Soil Available Cadmium

Fractal dimension indicates spatial continuity of variables within a scaling range. Figure 1 [Figure 1: see original paper] shows post-irrigation fractal dimensions

for each profile. All dimensions fell between 1 and 2, indicating that available cadmium values lie between strict spatial dependence and complete spatial independence, with soil structure exhibiting fractal characteristics.

Pre-irrigation fractal dimensions were 1.883, 1.776, 1.906, and 1.887 for profiles A, B, C, and D, respectively. Post-irrigation semivariance $[\gamma(h)]$ versus range (h) relationships followed fractal patterns. Profile B showed the highest fractal dimension (1.997), while dimensions decreased in profiles A (1.747), C (1.875), and D (1.840). This indicates that structural factors predominantly controlled the spatial variability of available cadmium in vertical distribution.

2.4 Vertical Distribution Analysis of Soil Available Cadmium

Contour maps effectively describe vertical distribution patterns. The experimental field sloped from northeast to southwest with silty clay soil, and irrigation flowed from south to north. Contour maps generated from experimental data are shown in Figure 2 [Figure 2: see original paper].

Post-irrigation, profiles A, B, and C showed predominantly east-west banded distributions, while profile D exhibited a patchy pattern. Available cadmium concentrations were highest in the surface 0–15 cm layer, demonstrating surface accumulation, with lower values at 25–35 cm depth. From profile A to D, contour line density decreased, variation amplitude diminished, and gradients weakened while direction changed. As irrigation water moved northward, topographic and soil particle size factors influenced distribution. All profiles showed decreased cadmium content post-irrigation, with weakened contour gradients trending toward patchy distribution, indicating migration, transformation, and adsorption processes created cumulative effects. Irrigation influenced cadmium distribution toward more homogeneous patterns with reduced variability.

2.5 Correlation Analysis Between Soil Properties and Available Cadmium

Correlation coefficients characterize relationships between variables. Table 3 presents correlations between moisture, organic matter, pH, and available cadmium. Available cadmium showed strong positive correlation with organic matter, moderate correlation with moisture, and strong negative correlation with pH. Higher organic matter content corresponded to greater available cadmium, while higher pH reduced available cadmium. Irrigation substantially altered the correlation between moisture and available cadmium and weakened relationships with organic matter and pH, indicating that available cadmium content is influenced by organic matter, ion exchange, irrigation water quality, and soil pH.

3 Discussion and Conclusions

This study combined geostatistics with traditional statistics to analyze spatial distribution and variability of available cadmium in vertical profiles following a single sewage irrigation event in a small-scale field. Results showed that available cadmium decreased to varying degrees after irrigation, with moderate spatial dispersion. Soil moisture and pH showed weak dispersion, while irrigation reduced spatial variability of all parameters. Despite cadmium in irrigation water, post-irrigation soil available cadmium did not increase as expected, indicating that leaching and migration exceeded inputs from irrigation water.

Pre-irrigation spatial variability was largely influenced by random factors, consistent with previous cadmium studies. However, post-irrigation fractal dimensions decreased and $C/(C+C)$ ratios fluctuated among profiles, indicating reduced random influence, weak spatial variability, and strong autocorrelation. The inconsistent variability among profiles reflects interactions among anthropogenic, structural, and environmental factors requiring further investigation. While fractal dimension and geostatistical methods have theoretical mathematical relationships, results were not entirely consistent in this study. Post-irrigation fractal and variability patterns in profiles B and D differed from theoretical expectations, possibly because soil is not an ideal fractal medium. Nevertheless, fractal analysis confirmed that geostatistical models are appropriate for spatial analysis of available cadmium at small scales.

Contour maps revealed banded vertical distributions influenced by topography and irrigation direction. Surface layers (0-15 cm) consistently showed higher concentrations than subsurface layers (30-40 cm), confirming cadmium enrichment in surface soils, consistent with most research findings. Vertical heterogeneity likely results from combined effects of soil physicochemical properties and root uptake.

Available cadmium correlated positively with organic matter, moderately with moisture, and negatively with pH, consistent with known influences of pH, organic matter, and clay content on heavy metal availability. Cadmium adsorption depends primarily on soil pH and carbonate content. Sewage irrigation significantly affected these factors while weakening their correlations with available cadmium, thereby influencing spatial variability.

The four profiles adequately reflected field-scale cadmium distribution. Single irrigation disturbance caused cadmium migration and redistribution, creating vertical spatial variability. As irrigation connects soil and plant systems, plant uptake represents a non-negligible factor in cadmium distribution. Integrating data from remediation plants or crops to analyze soil-plant system dynamics would advance phytoremediation research.

However, vertical distribution studies are limited by sampling depth and extent, restricting applicability to larger scales. Additionally, this study examined only a single irrigation event, whereas sewage irrigation contamination is a long-

term, gradual process requiring further investigation of water quality, timing, and frequency effects.

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