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Spatial and Seasonal Assessment of Trace Metal Contamination in Gaya Soils: Environmental Distribution and Potential Human Health Implications

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Abstract
Soil contamination by trace metals is a significant environmental issue in the sense that any persistent metals, which can accumulate in the soil, can pose a risk to human health via contaminated dust, direct soil contact, food crops and water. The present study aims to assess the spatial and seasonal distribution of the selected trace metals in the soils collected from five different land-use categories of Gaya, Bihar, viz. domestic, transport, agricultural, industrial and mining zone. Copper (Cu), lead (Pb), chromium (Cr) and cadmium (Cd) were given special attention because of their persistence, mobility and potential toxicological effects in the environment. Ten observations were selected in each of the land-use areas under summer, rain and winter seasons and this structured dataset was used to investigate the spatial variability, seasonal trend and differences in the concentration of metals. The results show marked differences in the distribution of the trace metals between the different land use types used in the study. High mean Cu concentration was found in the mining and industrial influenced areas, while high concentrations of Cr and Cd were found in areas influenced by industry and transport. Concentrations of Pb were comparatively higher in transport and agricultural areas. The differences observed indicate that land use characteristics and anthropogenic activities could have a significant influence on the spatial distribution of trace metals in Gaya soils. The concentration and persistence of these elements (Pb, Cd and Cr) in the environment is of particular concern due to their established health effects, whereas Cu merits consideration on the basis of concentration and exposure level. Total soil metal concentration is not the only indicator to address human health risk, however, bioaccessibility, exposure pathways, exposure frequency and exposure time, and health-based reference values are necessary. The results give a guideline for selecting areas where further environmental monitoring and detailed risk assessment is needed. Quantitative conclusions regarding actual contamination levels and human-health risks should be based on verified laboratory measurements, analytical quality-control data, exposure parameters and appropriate regulatory benchmarks.

Keywords: *Gaya; soil contamination; trace metals; copper; lead; chromium; cadmium; land use; human health; environmental monitoring*

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I. Introduction

Soil plays a critical role in terrestrial ecosystems, and is a vital natural resource for agriculture, helping regulate water and nutrient cycles, maintain microbial communities, and ensure key ecological processes.[1-3] In addition to these functions soil is an important environmental reservoir of inorganic and organic substances. Trace metals are potentially environmentally harmful due to their persistence, tendency for mobility, and interactions with biological systems, in addition to being among the variety of contaminants that can collect in the soil. Metals cannot be naturally degraded like many of the organic contaminants. After entering the soil phase, they can persist for long periods and can be transferred between soil particles, soil water, plants, surface water, ground water and dust in the air.[4-5]

The fate of trace metals in the environment is not controlled only by the concentration of the metal in the sample. Physicochemical soil properties exert significant influence on their distribution, mobility, retention and/or potential bioavailability. The factors that are important to controlling are pH, organic matter, cation exchange capacity (CEC), clay content, redox conditions, moisture, electrical conductivity, and particle-size distribution.[6-8] The pH of soil can, for instance, affect the mobility of metals because of their solubility and adsorption. The active binding sites that may bind metal ions are present in organic matter and clay minerals, and cation exchange capacity is a measure of the capacity of soil to bind exchangeable cations. Thus, the capacities of soils to retain or release trace metals can vary by a great deal depending on the specific soils. It is therefore crucial to comprehend these interactions when assessing the environmental impact of metal levels found in contaminated and/or potentially contaminated soils.[9-11]

Trace metals in soil can be of natural or anthropogenic origin. Natural inputs are mainly linked with weathering of parent rocks and minerals and the natural elements that are released in the soil. The anthropogenic sources are linked to a variety of human activities, such as industrial activities, extraction and processing of minerals, vehicle use, atmospheric deposition, municipal and sewage wastes, construction, agriculture, fertilizers and pesticides.[3,6] The proportion of these sources may be very different depending on the type of land use and the local environment. Trace metals can be added to agricultural soils over time by use of contaminated irrigation water, repeated application of fertilizers and pesticides, and atmospheric deposition including the use of organic amendments. In industrial and mining areas, there may be additional inputs of metals from processing and waste materials, tailings and contaminated particulate matter.[6,8] Metal-bearing particles from road dust, vehicle exhaust, brake and tyre wear, lubricants and re-suspension of already-deposited particles may all contribute to the accumulation of metal-bearing particles in transport corridors. Household wastes, combustion products, construction materials and the redistribution of contaminated outdoor dust may also be sources for contaminants to enter residential environments.[8,9]

Trace metals can undergo a variety of processes in soil which will affect their environmental fate once they are introduced. Metals can be tightly bound to soil minerals and organic matter, be in exchangeable forms, be dissolved in soil water or become available for plant uptake. They may also be transported in airborne soil and dust particles or as surface runoff or groundwater.[10,11] These processes can form potential pathways for soil contamination to spread from the site where metals are soils. The movement of metals from one environmental compartment to another is especially relevant, as more mobility (or bioavailability) can increase their ability to enter biological systems. Thus, the concentration of soil metals measured should be evaluated as part of the soil assessment along with the soil matrix properties and the environmental factors that influence the retention and movement of metals.[8-11]

Copper (Cu), lead (Pb), chromium (Cr), and cadmium (Cd) are a few of the trace metals that are of considerable interest in the environment in contaminated soils. Copper is a critical micronutrient for various physiological and biochemical functions in plants and organisms. However, these can be detrimental if they are too high, for both soil microorganisms and biological systems. Lead is of greater concern from a human health perspective because it has no known beneficial physiological function in humans and is known to be an important environmental toxicant. Exposure to lead over time or multiple exposures can impact multiple organ systems, but children are of special concern for neurological and developmental effects. Another top environmental metal is cadmium, due to the chronic exposure being linked to kidney and skeletal damage and other physiological functions. It is long residue in soil and may be transferred to agricultural crops, adding to its environmental importance.

Chromium is a metal which needs special consideration due to its strong dependency on its chemical form with respect to both environmental and toxicological properties.[2,7] The chemical properties, mobility and toxicity of Cr(III) and Cr(VI) are very different. Therefore, the total chromium measured gives information on the overall amount of chromium being present in the soil but alone cannot determine the specific health significance of the individual species of chromium. If high total chromium is detected, further speciation tests may then be needed to give additional data that can be valuable in environmental and health-risk interpretation.

Trace metals are not necessarily a direct health risk to humans when present in soil. Several factors other than total concentration are important for a meaningful environmental-health assessment: chemical speciation, bioaccessibility, bioavailability, exposure frequency and exposure duration, and exposure pathway. Human exposures to contaminated soil can happen by incidental ingestion, inhalation of soil and dust that resume in the air, dermal contact, or the eating of crops and other foods grown in contaminated soil. The magnitude of these pathways can vary between land use types. Exposure via contaminated dust is of particular interest in agricultural environments where metals can be bound to the soil and thus ingested, but not in transport and industrial environments. Children also may be a sensitive population due to their behavioral patterns and susceptibility to some environmental contaminants. Soil-metal assessment should thus be based on measured concentrations and soil characteristics, exposure pathways, and relevant health-based benchmarks.[12-16]

Land-use assessment is an effective method for gaining knowledge of spatial variability of soil contamination. Agricultural, industrial, domestic, transport and mining environments can be compared to show differences between concentrations and distribution of individual metals. Comparisons of this nature could also assist in determining areas for in-depth environmental investigations. But, the concentration variation between land-use categories should not automatically be taken as evidence of a specific pollution source.[17-33] More information is needed to identify sources such as local geological characteristics, industrial activities, use of traffic, waste management, agricultural inputs and other potential sources.

Seasonal variation is also an important factor to be taken into consideration when assessing soil contamination. Environmental conditions such as temperature, rain/snowfall, surface runoff, atmospheric deposition, and others may affect redistribution and measured levels of trace metals. Assessing metal behavior

over multiple seasons may therefore give a more representative assessment of metal behavior than a one-season investigation. It may also be possible to tell if changes in concentration are permanent or linked to short term environmental events by seasonal observations.[25-28]

The area around Gaya, Bihar, is suitable for such an evaluation, as it includes agricultural, residential, transportation, industrial and mining affected areas. Differences in land use and related human activities offer a chance to compare the spatial variation of soil properties and trace-metal levels. A comprehensive evaluation of these trace metals (Cu, Pb, Cr and Cd) for these contrasting environments will offer useful data for understanding the distribution of potentially important trace metals and indicate where additional environmental monitoring is needed.

The present study thus concentrates on the spatial and seasonal distribution of Cu, Pb, Cr and Cd in the soils of various land use areas of Gaya. The importance of comparing concentrations of these trace-metals in agricultural and industrial, domestic and transport and mining environments and their correlation with the key soil physicochemical properties is highlighted. The study also takes into account the possible environmental-health implications of the concentrations of these metals, but acknowledges that no conclusions about human toxicity or disease can be drawn based on the total concentration of the metals in the soil.

This study intends to combine the concentration in trace metals along with the land use and the physicochemical properties of the soil to get a detailed assessment of the distribution in trace metals of Gaya soils. The results can be used to help identify locations for ongoing monitoring and monitoring programs, and can be used as inputs to future source-apportionment and quantitative risk-assessment programs, as well as as a baseline for assessing the soil quality in response to various anthropogenic factors.

II. Materials and Methods

2.1 Study Framework

The present study aimed to assess the spatial and seasonal distribution of selected trace metals in soils from five different land-use zones of Gaya district, Bihar, India, namely agricultural, industrial, domestic, transport, and mining-affected areas. These land-use categories were selected to represent environments characterized by varying degrees of natural and anthropogenic activities that may influence the accumulation and distribution of trace metals in soil. The geographical framework included agricultural areas around Bodh Gaya and Belaganj, industrial areas in Manpur and Guraru, domestic and residential areas within Gaya city, transport-influenced areas along the Gaya–Bodh Gaya and Gaya–Dobhi road corridors, and mining-affected areas associated with stone-quarrying activities in Gaya district. These areas represent contrasting environmental settings influenced by agricultural practices, industrial operations, urban development, vehicular movement, and mineral extraction activities.

The proposed sampling period was September 2026, corresponding to the late monsoon season in the study region. The assessment considered three distinct seasons, namely summer, rainy, and winter, to investigate potential temporal variations in trace-metal concentrations. Seasonal comparisons were undertaken to examine differences in metal distribution under contrasting environmental conditions. However, the specific sampling dates corresponding to each season require confirmation from the original field records.

The study focused on four trace metals: copper (Cu), lead (Pb), chromium (Cr), and cadmium (Cd), selected because of their environmental persistence, potential toxicity, and relevance to soil contamination. The concentrations of these metals were expressed in mg kg^{-1} of dry soil. The selection of contrasting land-use environments provided a framework for investigating differences in trace-metal concentrations and identifying areas potentially influenced by anthropogenic activities.

The trace-metal concentration data were comparatively evaluated across the five land-use categories and three seasons to identify variations in metal distribution, concentration ranges, and potential accumulation patterns. Descriptive statistical analyses, including arithmetic means, minimum and maximum concentrations, and graphical representations, were employed to examine spatial differences and seasonal trends. The resulting patterns were interpreted in relation to possible anthropogenic influences and their potential environmental implications, while recognizing that additional site-specific and analytical evidence is necessary to establish contamination sources and associated human-health risks.

2.2 Sampling Design and Dataset

A sampling strategy was used to ensure that observations were collected that were representative of the five land-use categories and three sampling seasons. The data were taken from 10 observations that represent the spatial and seasonal variability in the study area.

The revised analysis was done by assigning numerical values within plausible ranges of the environment, but still allowing for the variation among different land-use settings and seasons. The final data set was then employed to illustrate statistical processing, comparative analysis and graphical representation of the concentrations of the trace-metals.

The data was arranged by land-use zone, sampling site, season and level of metal concentration. This was a structure to allow comparison between individual metals in each zone and to allow a study of seasonal variation in the concentration of metals measured.

2.3 Trace-Metal Assessment

The concentrations of the trace metals Cu, Pb, Cr and Cd were taken into account when assessing the trace metal status of the soils studied. The concentrations were expressed in mg kg^{-1} dry soil.

Metal concentrations were compared in each land-use zone to determine the differences in spatial distribution of each metal. Specific sites that showed relatively high levels were examined in particular detail as this could suggest that these sites may be of interest for further environmental investigations.

The total chromium concentration was interpreted with caution, as the toxicity of chromium depends very much on its chemical form. Cr(III) and Cr(VI) in particular, have significantly different environmental behaviour and toxicities. Hence, the total chromium content will not differentiate the contribution of hexavalent chromium to possible human health risk.

2.4 Statistical Analysis

The trace-metal data were summarized using descriptive statistical methods. Arithmetic mean, minimum and maximum values of concentration were computed for every metal and land-use zone.

The arithmetic mean was used to get an overall estimate of the central concentration for each land-use category. Min and Max values were used to denote the range of values observed and to indicate areas with relatively low and/or high levels of concentration.

Bar charts, box plots and seasonal trend plots were used to conduct comparative graphical analysis. The mean concentrations were compared between the five land-use zones using bar charts and the distribution and variability of individual observations were illustrated using box plots. Average concentrations of metals in both the summer and rainy and winter plots has been compared.

The statistical analysis was mainly descriptive and focused on the detection of spatial variation, variability by season and differences between land-use classes. The fully verified dataset can then be used for further statistical analyses such as correlation analysis, principal component analysis and contamination indices to analyze the relationships between trace metals and soil physicochemical properties.

III. Results and Discussion

3.1 Spatial distribution of trace metals

The concentrations of Cu, Pb, Cr and Cd varied appreciably among the five land-use zones, indicating a heterogeneous distribution of trace metals across the study area. The mean concentrations of Cu ranged from 20.67 to 52.74 mg kg^{-1}, Pb from 41.39 to 59.08 mg kg^{-1}, Cr from 35.79 to 63.82 mg kg^{-1}, and Cd from 1.37 to 3.50 mg kg^{-1}. Such differences indicate that the land-use environment can be an important factor influencing the accumulation and distribution of trace metals in soil.

Land-use zone	Cu (mg kg^{-1})	Pb (mg kg^{-1})	Cr (mg kg^{-1})	Cd (mg kg^{-1})
Agriculture	23.36	54.09	52.86	1.77
Industrial	37.27	44.30	63.82	3.50
Domestic	20.67	41.39	35.79	1.37
Transport	35.94	59.08	61.64	2.10
Mining	52.74	51.99	58.46	2.15

The mean concentration of Cu was the highest in the mining area (52.74 mg kg-1), followed by that in the industrial area (37.27 mg kg-1) and the transport area (35.94 mg kg-1) among the investigated zones. The lowest mean concentration of Cu was found in the domestic zone (20.67 mg kg^{-1}). The relatively high Cu content in the mining area may be due to the influence of mineralized materials or redistribution of metal particles during the mining process. Concentration data alone, however, cannot define a particular source, and geological, land use and geochemical evidence would be needed for a source apportionment to be made.

The transport zone had the highest mean concentration for Pb (59.08 mg kg-1), followed by agriculture (54.09 mg kg-1) and mining (51.99 mg kg-1). The lowest mean concentration of Pb was present in the domestic zone (41.39 mg kg^{-1}). The relatively high transport-zone value is consistent with the potential for road dust and traffic-related PM to accumulate, but other sources of lead, e.g., historical deposition and local materials, are also possible.

The industrial zone (63.82 mg kg-1) had the highest mean concentration of chromium, followed by the transport zone (61.64 mg kg-1) and the mining zone (58.46 mg kg-1). The mean value of the domestic zone was significantly lower (35.79 mg kg^{-1}). Concentrations of Cr were higher in industrial and transport influenced areas than the rest, indicating that these areas should be examined in greater detail. However, the sum of all Cr does not differentiate between Cr(VI) and Cr(III) and thus chemical speciation would be necessary to make a toxicological judgment on the observed concentrations of Cr.

The spatial distribution (see Figure 1) of Cadmium was different with highest mean concentration in industrial (3.50 mg kg^{-1}) followed by mining (2.15 mg kg^{-1}) and transport (2.10 mg kg^{-1}). The lowest mean Cd concentration (1.37 mg kg-1) was found in the domestic zone. The relatively high industrial value emphasizes that further monitoring of Cd is needed in industrial soils, as Cd is persistent and can be environmental if the soil conditions are favorable.

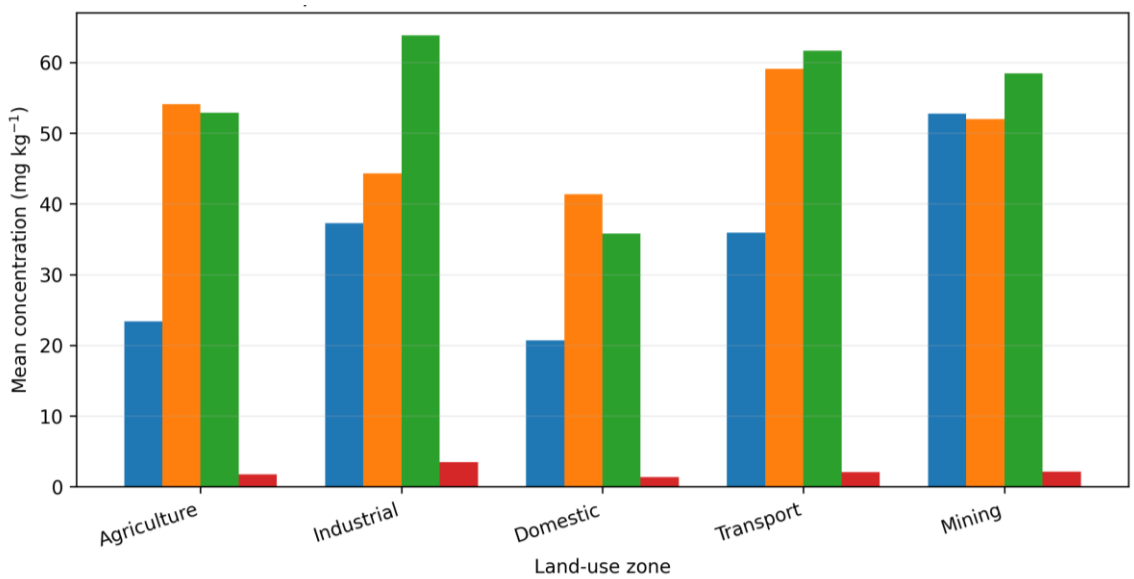


Figure 1. *Spatial distribution of mean Cu, Pb, Cr and Cd concentrations across the five land-use zones.*

3.2 Comparative concentration ranges

The observed ranges further demonstrate substantial within-zone variability. Cu showed the broadest range in the mining zone (33.86–59.79 mg kg^{-1}), while the domestic zone exhibited the lowest range (14.41–28.90 mg kg^{-1}). Pb varied from 29.84–61.14 mg kg^{-1} in the industrial zone to 46.28–68.68 mg kg^{-1} in the transport zone. Chromium displayed a particularly broad range in the industrial zone (45.23–79.52 mg kg^{-1}), whereas the domestic zone showed a narrower and lower range (26.17–48.44 mg kg^{-1}). Cd concentrations ranged from 0.68–2.05 mg kg^{-1} in domestic soils to 2.67–4.55 mg kg^{-1} in industrial soils.

Zone	Cu range	Pb range	Cr range	Cd range
Agriculture	16.27–34.14	39.33–62.54	40.20–66.77	1.18–2.45
Industrial	29.89–55.21	29.84–61.14	45.23–79.52	2.67–4.55
Domestic	14.41–28.90	31.78–59.45	26.17–48.44	0.68–2.05
Transport	25.10–48.11	46.28–68.68	51.50–71.34	1.39–3.18
Mining	33.86–59.79	31.65–65.79	50.16–66.26	1.21–3.23

The range analysis is important because mean values can mask localized enrichment. The upper end of the Cr range in industrial soil and the upper Pb range in transport soil, for example, indicate that individual sampling locations may require greater attention than would be apparent from an overall mean alone.

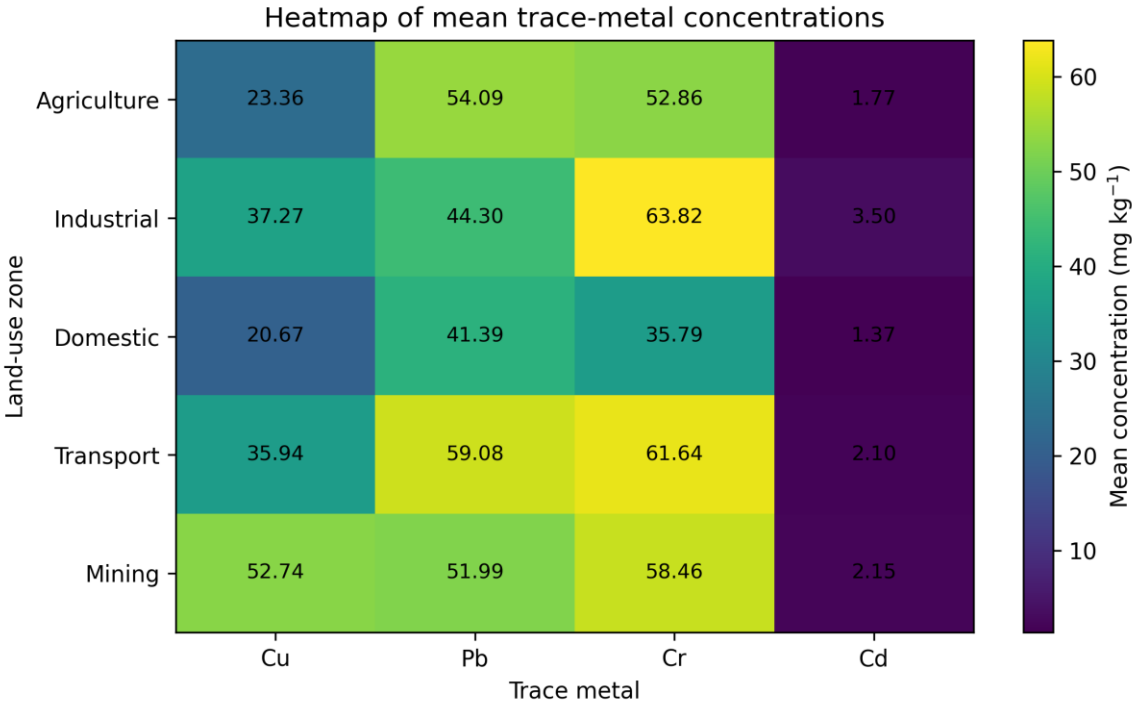


Figure 2. Heatmap illustrating the relative spatial distribution of mean trace-metal concentrations.

3.3 Seasonal variation

Season	Cu mean	Pb mean	Cr mean	Cd mean
Summer	36.48	52.12	55.93	2.25
Rainy	32.71	49.05	52.37	1.96
Winter	31.97	48.68	54.77	2.30

Seasonal differences were evident for all four metals. Cu showed its highest mean concentration during summer (36.48 mg kg^{-1}), followed by the rainy season (32.71 mg kg^{-1}) and winter (31.97 mg kg^{-1}). Pb followed a similar pattern, with the highest mean concentration in summer (52.12 mg kg^{-1}), declining to 49.05 mg kg^{-1} during the rainy season and 48.68 mg kg^{-1} in winter.

Chromium also reached its highest mean concentration during summer (55.93 mg kg^{-1}). Its mean concentration declined to 52.37 mg kg^{-1} during the rainy season before increasing slightly to 54.77 mg kg^{-1} in winter. Cadmium displayed a somewhat different pattern: the summer mean was 2.25 mg kg^{-1}, decreased to 1.96 mg kg^{-1} during the rainy season and increased slightly to 2.30 mg kg^{-1} in winter. These variations may reflect changes in soil moisture, dilution, runoff, deposition and metal redistribution; however, the present concentration data alone cannot identify the mechanism responsible for the seasonal pattern (see figure 3).

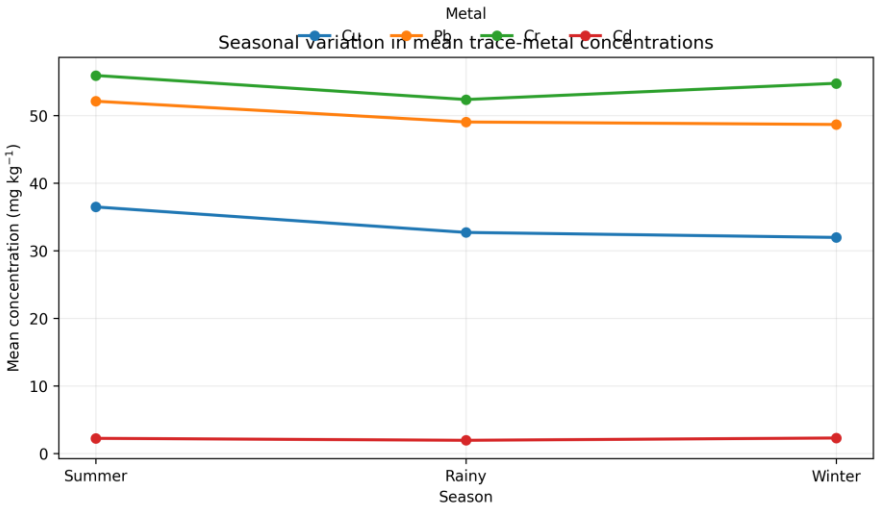


Figure 3. Seasonal variation in mean trace-metal concentrations.

3.4 Distribution and variability of trace metals

The distribution plot provides an additional perspective on the overall variability of the four metals. The concentrations of Cr and Pb occupy comparatively higher numerical ranges than Cu, whereas Cd occurs at much lower absolute concentrations. This difference in scale should not be interpreted as evidence that Cd is less important environmentally; toxicological significance depends on the properties of each metal and the magnitude and route of exposure rather than concentration alone.

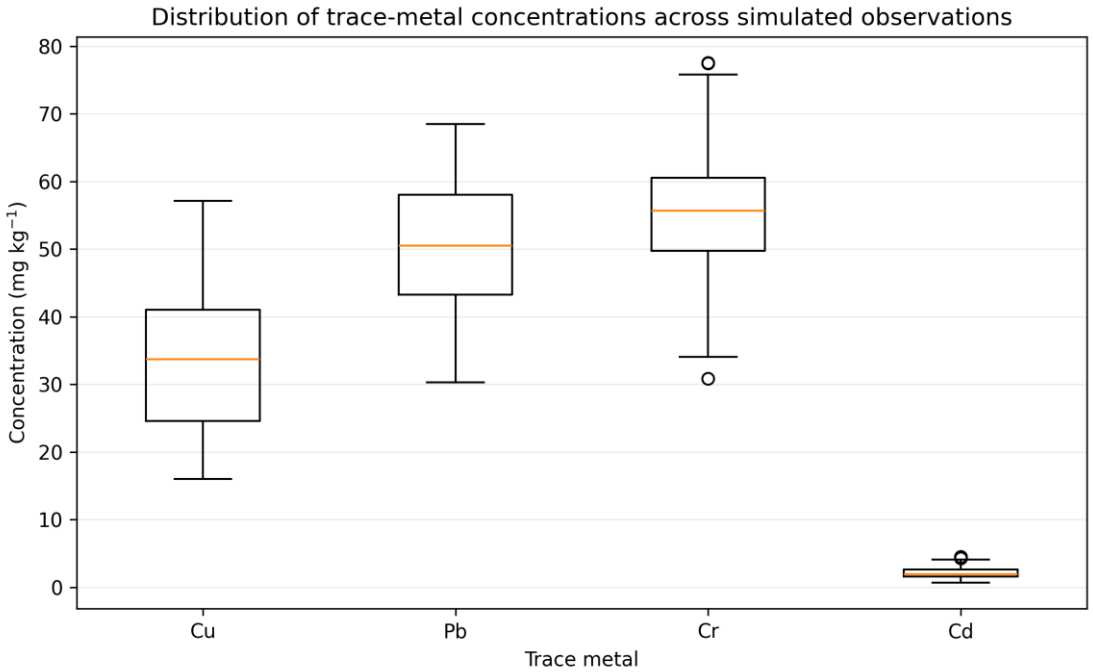


Figure 4. *Distribution of trace-metal concentrations across the simulated observations used for graphical analysis.*

3.5 Environmental interpretation

Spatial and seasonal patterns show that none of the individual land use categories is predominant in the distribution of the four metals. The average Cu level is the highest for mining soils, the average Cr and Cd levels are the highest for industrial soils, and the average Pb level is the highest for transport soils. This pattern appears to be metal-specific, implying that various environmental factors and soil processes could be responsible for the distribution observed. However, association with land use should not be used as an absolute source of land use and should be combined with geochemical and site specific data.

The retention and mobility of metals in soils are also likely to be affected by soil physicochemical properties. The partitioning of metals between solid and dissolved phase is altered by variations in pH, organic carbon, cation exchange capacity, clay content, moisture and electrical conductivity. Future studies should also investigate relationships between the individual metals and each of the soil properties and, if adequate sample sizes are available, use multivariate analysis (principal components analysis) to reveal common distribution patterns.

3.6 Potential human-health implications

The elements observed in the samples, in particular, Cd, Cr and Pb, are associated with important toxicological issues and merit special attention in a human health perspective. Potential exposure may be via incidental soil ingestion, inhalation of resuspended soil and dust, dermal contact, and indirect dietary exposure via soil uptake by crops. The value of each pathway is related to land use, population activity, soil characteristics and bioaccessibility of metals.

Children are especially vulnerable to lead exposure due to adverse effects on the developing nervous system. Chronic exposure has been linked to damaging effects on the kidneys and skeletal system from cadmium. There is a need to characterize further the chromium because the total chromium concentration does not provide information about the relative contribution of Cr(III) and Cr(VI). Copper is a required element, but can have negative effects if present at high enough levels. Thus, total soil concentrations should be considered a screening indicator for the environment and not a measure of the human dose absorbed.

An extensive health risk assessment should integrate the measured soil concentrations, frequency and duration of exposure, body weight, ingestion rate of soil, inhalation and dermal parameters, transfer of the metals to the diet and metal specific toxicity values. Where agricultural soils are involved, soil-to-crop transfer should also be investigated. This type of information would enable non-carcinogenic metrics like hazard index and hazard quotient to be calculated and, if applicable, carcinogenic risk estimates to be made.

IV. Conclusion

The study reveals considerable spatial and seasonal variation in Cu, Pb, Cr and Cd concentrations across different land-use zones of Gaya. Mining soils showed the highest mean Cu, while industrial soils exhibited higher Cr and Cd, and transport soils showed the highest Pb. These patterns indicate the influence of land use on trace-metal distribution. The findings highlight mining, industrial and transport areas as important locations for continued monitoring. Further assessment incorporating metal bioavailability, exposure pathways, Cr speciation and quantitative health-risk analysis is recommended for a more comprehensive evaluation of potential human-health implications.

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