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Geostatistical mapping of soil characteristics to uncover geographic patterns of CKDu in dry zone, Sri Lanka

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Abstract
Addressing contemporary and future public health challenges necessitates a comprehensive understanding of the role of soils, particularly in relation to the rising incidence of Chronic Kidney Disease of Unknown etiology (CKDu) in Sri Lanka. This study investigates the spatial distribution patterns of nephrotoxic heavy metals in soils within CKDu-endemic regions, employing spatial interpolation and spatial autocorrelation analyses to inform evidence-based policy development for disease prevention. The concentration hierarchy of heavy metals in soils from CKDu-affected areas was observed as Zn > Cu > Pb > As > Cr > Cd. Notably, the levels of Cd, Pb, and Cr were significantly elevated in hotspot regions compared to reference (non-endemic) sites. Spatial analysis using Global Moran's Index (MI) revealed a clustered distribution of cadmium (MI = 0.3145), particularly in areas under paddy cultivation, suggesting a strong association between agricultural practices and cadmium accumulation. In contrast, Pb, As, and Cr exhibited more randomized spatial distributions at comparatively lower concentrations. These findings underscore the critical concern of heavy metal accumulation—especially cadmium—in agricultural soils and its potential entry into the human food chain via rice cultivation. The implications for public health are profound, highlighting the need for targeted soil management and agricultural interventions as part of a sustainable strategy to mitigate CKDu prevalence in Sri Lanka.

Keywords*: Soil contamination, Nephrotoxic heavy metals, Spatial analysis, Global Moran's Index, CKDu*

Introduction

The soil system plays a fundamental role in terrestrial ecosystem functioning, particularly through its capacity to store and transmit water, which regulates both plant-available water and the transport of environmental pollutants to surface and groundwater resources. However, the accumulation of toxic substances—such as heavy metals/metalloids, radioactive isotopes, and organic xenobiotics—in soils has raised critical concerns due to their persistence, bioaccumulation potential, and adverse impacts on ecosystem and human health (Brevik et al., 2015). Given these implications, soil is increasingly recognized as a finite and non-renewable natural resource on a human timescale (Robinson et al., 2014), warranting systematic scientific investigations into its potential linkages with public health outcomes. Since the mid-1990s, Sri Lanka has witnessed the emergence of a distinct form of chronic kidney disease of uncertain etiology (CKDu), predominantly affecting rural agrarian populations in the upper dry zone, with recent reports indicating an expansion into the lower dry zone (Wijewickrama et al., 2019). Unlike conventional CKD, CKDu manifests in the absence of traditional etiological factors, such as diabetes mellitus and hypertension, suggesting environmentally mediated pathogenesis. The spatial clustering of CKDu, its confinement largely to farming communities, and the

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renal histopathological findings strongly implicate chronic exposure to environmental nephrotoxicants, potentially derived from soil-related pathways, in the disease's onset and progression. Despite extensive epidemiological and environmental research, the etiology of CKDu remains unresolved, highlighting the necessity to investigate multifactorial and context-specific soil exposures. Comparative analyses between CKDu-endemic and non-endemic areas under similar geoclimatic and agroecological conditions could provide valuable insights into the geochemical and anthropogenic factors influencing disease distribution. Existing research on soil–health interrelationships remains scarce, fragmented, and poorly integrated, underscoring the need for a holistic and multidisciplinary framework that encompasses diverse economic, geographic, and environmental contexts (Brevik and Burgess, 2012). To accurately characterize soil nephrotoxicity and its spatial associations with CKDu prevalence, the adoption of advanced geospatial analytical approaches, such as spatial interpolation, spatial autocorrelation, and geostatistical modeling, is imperative. These methods offer superior resolution over traditional statistical analyses, enabling the identification of spatial heterogeneity, exposure gradients, and potential causative hotspots (Wang and Luo, 2012). Such integrative analytical frameworks can substantially contribute to unraveling disease etiologies and provide a scientific basis for predictive modeling and preventive policy formulation, particularly targeting vulnerable rural populations disproportionately affected by CKDu.

Methodology

Study areas and site selection

Girandurukotte Grama Niladhari Division (GND) [81.020176E, 7.465041N], Badulla district, Uva province, Sri Lanka (Fig.1a) was identified for the sampling as the CKDu endemic area according to the data of the Ministry of Health and Nutrition, Sri Lanka. Dambethalawa GND [81.51630E, 7.309013N] (Fig.1b), Ampara district was selected as the reference site where no CKDu cases have been reported but have similar climate conditions, which are present in the selected CKDu prevalence area. The Girandurukotte area is a significant CKDu hotspot due to its long-standing dependence on intensive paddy cultivation, where continuous use of phosphate fertilizers and agrochemicals has led to elevated heavy metal accumulation in soils and water sources. Moreover, its semi-arid climatic conditions and reliance on shallow groundwater for drinking and irrigation enhance human exposure to nephrotoxic elements, making it a critical region for CKDu research and mitigation.

Sample collection

Soil/Sediment sample collection and pH-EC measurements. Thirty (30) soil samples were collected from each GND using the supervised classification of ArcMap 10.8 software with the latest Arial satellite images and 10 composite sediment samples were collected from Ulhitiya reservoir within the CKDu hotspot. The suspensions (1:2 soil-deionized water) were prepared using collected soil samples separately and the pH and EC of the samples were measured using a calibrated multi-parameter.

Preparation and analysis of heavy metals in soil samples

Each soil or sediment sample was digested using ETHOS EASY microwave digester by adding concen-

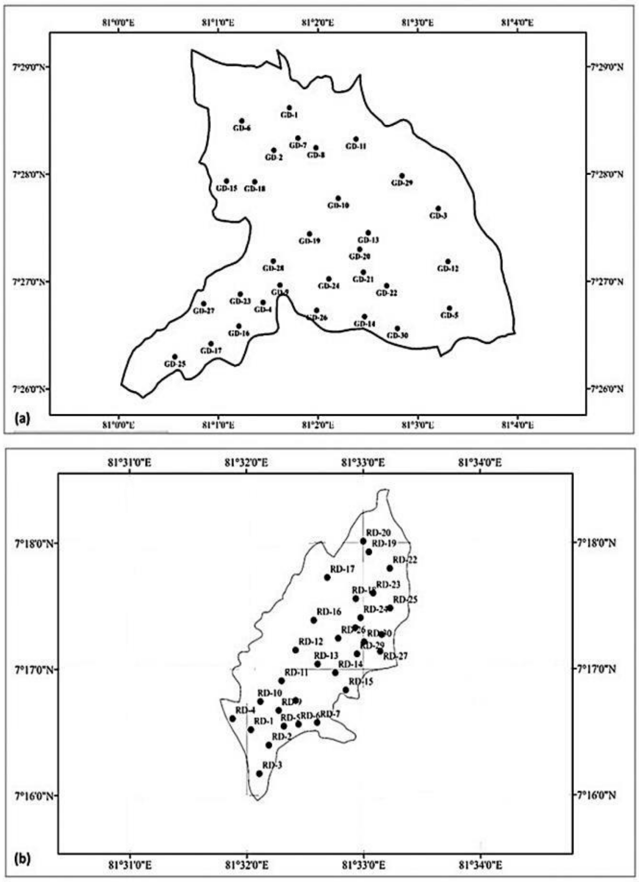

Figure 1. *Maps showing the sampling areas with sampling points of (a) Girandurukotte GND (CKDu hotspot), Badulla district, Uva province, and (b) Dambethalawa GND (the reference), Ampara district, Sri Lanka.*

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trated HNO_3. The concentrations of heavy metals in digested soils were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS-7800-Agilent, Germany). Multi-element ICP-MS standards (AccuStandard, USA) were used for instrumental calibration and a set of calibration solutions was prepared, including 100.00, 500.00, 1000.00, and 2000.00 μg/L for metal analysis of digested soil/sediment samples.

Statistical data analysis and Geo-statistical analysis

Descriptive, parametric, and non-parametric statistical analyses were conducted using SPSS software to evaluate variations and relationships among measured parameters. Spatial interpolation of heavy metal distributions was performed using the Inverse Distance Weighted (IDW) algorithm, providing a continuous spatial representation of concentration gradients. Furthermore, spatial autocorrelation analysis employying Moran's Index (MI) within ArcMap 10.8 was utilized to assess the degree and pattern of spatial clustering or dispersion of heavy metals across the study area.

Results and Discussion

Soil physicochemical parameters and elemental composition play a critical role in determining the environmental behavior and bioavailability of potential nephrotoxicants within agroecosystems. Variations in soil pH, electrical conductivity, and heavy metal/metalloid content can profoundly influence metal speciation, solubility, and mobility—ultimately affecting plant uptake, trophic transfer, and human exposure pathways. Therefore, understanding the geochemical signatures of soils in CKDu-prevalent regions is essential for elucidating the potential environmental contributions to disease etiology and spatial risk differentiation between endemic and non-endemic areas. The pH of soil samples collected from the Girandurukotte Grama Niladhari Division (GND) exhibited substantial variability, ranging from 4.27 to 8.31, with a mean value of 6.25, whereas the reference soils recorded a mean pH of 5.12, reflecting moderate to slightly acidic conditions. Such variability may arise from leaching of base-forming cations (Ca^{2+}, Mg^{2+}), decomposition of organic residues, or the application of synthetic agrochemicals, all of which can alter soil acid–base equilibria and buffering capacity. The mean electrical conductivity (EC) of soils in the CKDu hotspot was 137.74 μS/cm, significantly higher than that of the reference soils (58.85 μS/cm, $p = 0.003$). Elevated EC levels are indicative of a higher ionic load in the soil solution, possibly resulting from fertilizer accumulation, irrigation practices, or natural geochemical processes that enhance solute migration and salt enrichment. Heavy metal and metalloid analyses revealed the predominance of Pb, Cr, As, Zn, Cd, and Cu in soils of the CKDu hotspot. Among these, Zn and Cu—both dietary essential trace elements—were present at notably elevated concentrations, with mean values of 2267.13 ±1.53 mg/kg and 99.43 ±2.83 mg/kg, respectively. The order of heavy metal abundance in soils followed the sequence Zn > Cu > Pb > As > Cr > Cd, indicating the dominance of Zn and Cu, and comparatively lower levels of Cd within the In contrast, nonessential toxic elements were also present in considerable amounts, with mean concentrations of Pb (24.65 ±2.19 mg/kg), Cd (2.10 ±0.49 mg/kg), As (39.52 ±6.90 mg/kg), and Cr (36.40 ± 4.59 mg/kg). CKDu hotspot. Statistical analysis confirmed significantly higher concentrations of Cd, Pb, and Cr in the Girandurukotte soils compared to the reference ($p < 0.05$), with respective p-values of 0.017, 0.024, and 0.426. Although mean concentra-tions of most metals remained below the maximum allowable concentrations (MACs) stipulated in inter-national soil quality standards (Table 1), As and Zn exceeded the permissible limits in both study loca-tions, suggesting potential ecological and public health relevance.

Table 1
Comparison of concentrations of the selected heavy etal/metalloids in soils collected from the CKDu hotspot with the reference and maximum allowable concentration (MAC) values.

Content in the CKDu hotspot (mg/kg)		Content in the reference (mg/kg)		MAC	P-value
Mean	±SD	Mean	±SD		
2.10	0.49	0.70	0.03	1-5	0.017
24.65	2.19	12.36	1.05	20-300	0.024
39.52	6.90	31.21	4.47	15–20	1.240
36.40	4.59	15.90	2.35	50-200	0.426
2267.13	1.53	2164.22	2.47	100-300	0.620
99.43	2.83	93.48	1.73	60-150	1.380

SD: standard deviation, MAC: maximum allowable concentrations (Kabata-Pendias, 2011). Metal values are reported in mg/kg, p-value generated from paired t-test performed on the data set

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Spatial interpolation analysis further demonstrated distinct spatial variability in heavy metal distribution. The Cd content across the Girandurukotte region ranged from 0.5020 to 5.4988 mg/kg, with the highest concentration recorded at sampling location GD-4 (Fig. 2b). Similarly, Pb concentrations ranged from 10.0341 to 82.6672 mg/kg, with GD-25 exhibiting the maximum Pb accumulation (Fig. 2a). These localized enrichment zones likely reflect the combined influence of anthropogenic inputs, soil geochemical heterogeneity, and hydrogeological transport mechanisms, which together modulate the spatial distribution and potential bioavailability of nephrotoxic metals within CKDu-affected landscapes. Arsenic content in soil ranged between 15.9245 mg/kg to 74.3527 mg/kg, and GD-4, GD-5, GD-6, GD-18, and GD-23 sampling points were shown the highest Arsenic concentrations in the soil of the CKDu hotspot (Fig. 2c). Furthermore, the highest soil Chromium content was found in the GD-23 sampling location, and the Cr content in the area was ranged between 11.0242 mg/kg to 147.1613mg/kg (Figure 2d).

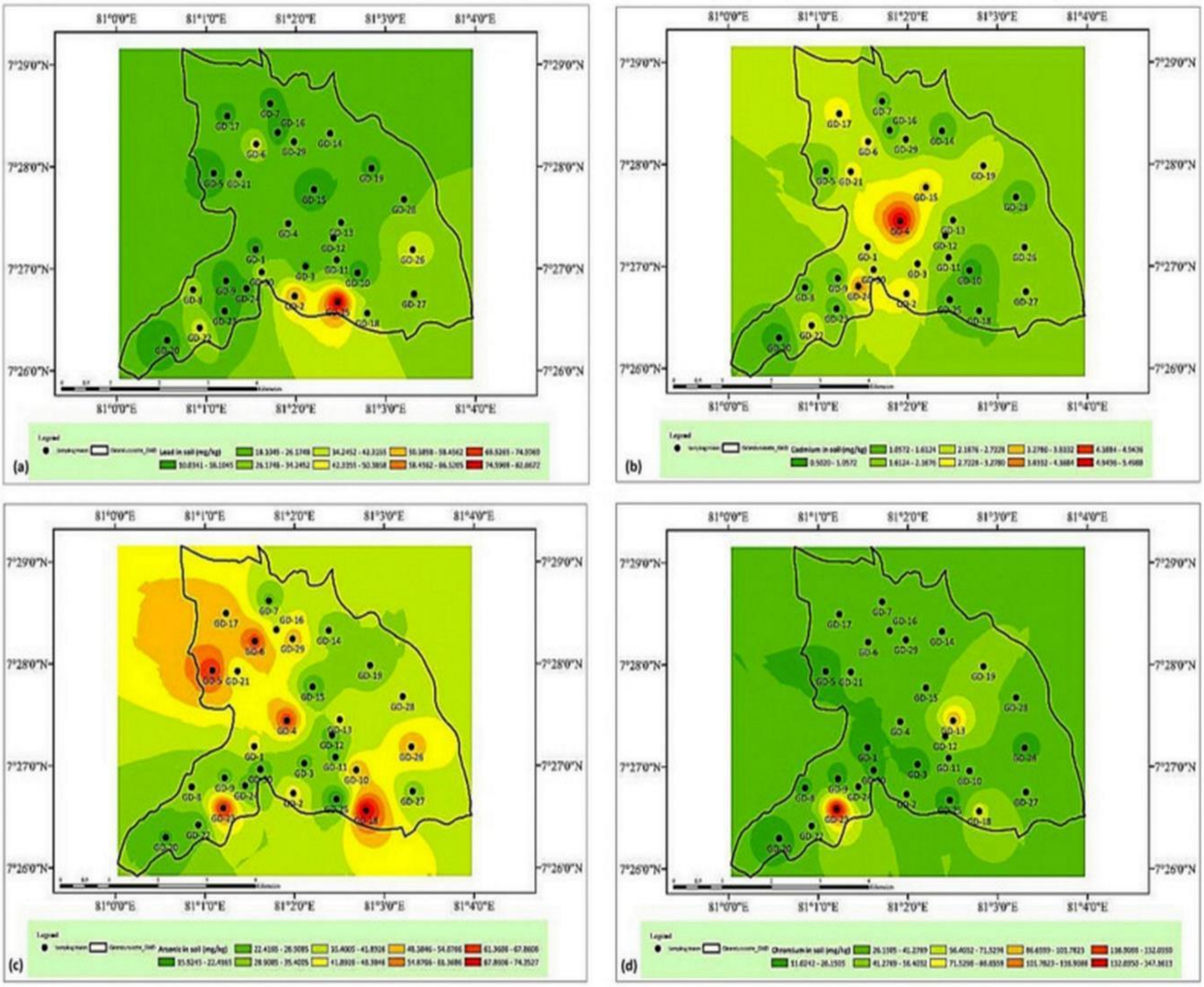

Figure 2. *Spatial distribution patterns of (a) Lead (b) Cadmium and (c) Arsenic and (d) Chromium in the CKDu hotspot by Inverse Distance Weighted (IDW) Interpolation for soil analysis.*

Local geo-statistics like the IDW tool assess each feature within the context of neighboring elements. Therefore, global geo-statistics like the Spatial Autocorrelation (Global Moran's I) tool should be used to evaluate the overall pattern and trend of the data. They are most effective when the spatial distribution is more or less consistent across the study area. The spatial autocorrelation tool in ArcMap 10.2.2 helps understand the degree to which one object is similar to other nearby objects based on both feature locations

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Studying the composition of surface sediments of the aquatic environment allowed us to understand the terrestrial materials' fate transported into a basin and the factors responsible for controlling the distribution and geochemistry of sediments. The spatial distribution depends on hydrodynamic conditions, type of deposits, and metal sources. Moreover, the shape of the reservoir and the biochemical processes modify the heavy metal deposition. However, according to the IDW interop-lation, which was estimated by ArcMap software for the sediments in both reservoirs (Figure 04), the detected heavy metal loads in bottom sediments were high in Ulhitya reservoir (ND (Not detected (>LOD) range to 80.0000 mg/kg) than the reference (Namaloya reservoir) (ND (>LOD) range to 20.0000 mg/kg). The highest concentrations of As and Cr have been detected generally in the vicinity of agricultural runoff inflow in both reservoirs. Interestingly, Ulitiya reservoir sediments showed an inverse spatial pattern for Cd and Pb compared with the reference, and sediment Pb and Cd in Ulhitiya were detected in significantly deficient levels than As and Cr. The binding of these metals with organic matter and minerals, mainly clay in bottom sediments, can minimize their toxicity. However, heavy metals are not permanently bound to sediments, and they may be released into the water column when the environmental conditions change (e.g., temperature and pH) or when sediments undergo other physical or biological disturbances. Furthermore, reservoir con-struction generally leads to increased residence time,

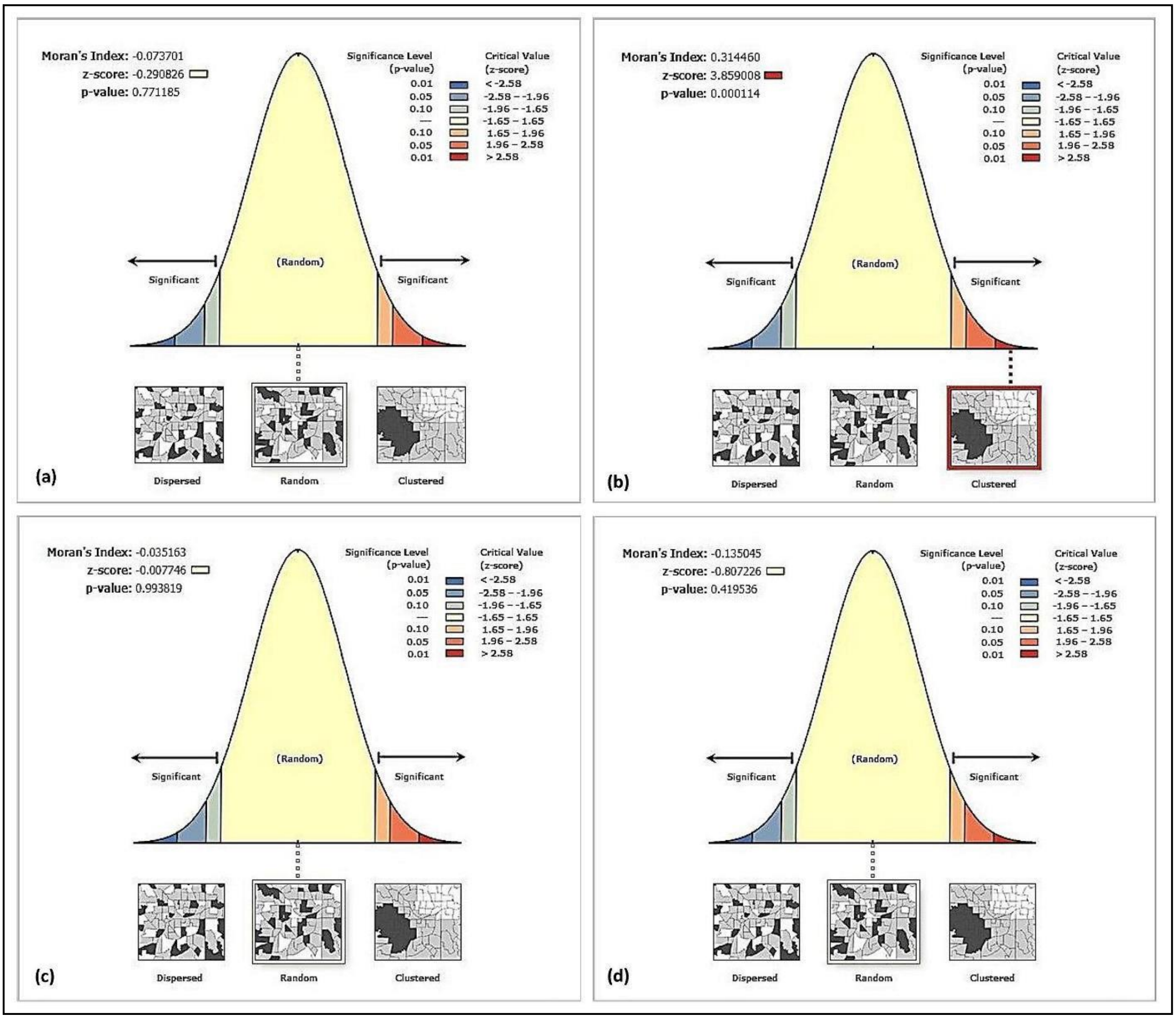

Figure 3. *Spatial autocorrelation results with Global Moran's Indexes of (a) Lead (b) Cadmium and (c) Arsenic and (d) Chromium in the CKDu hotspot for soil analysis.*

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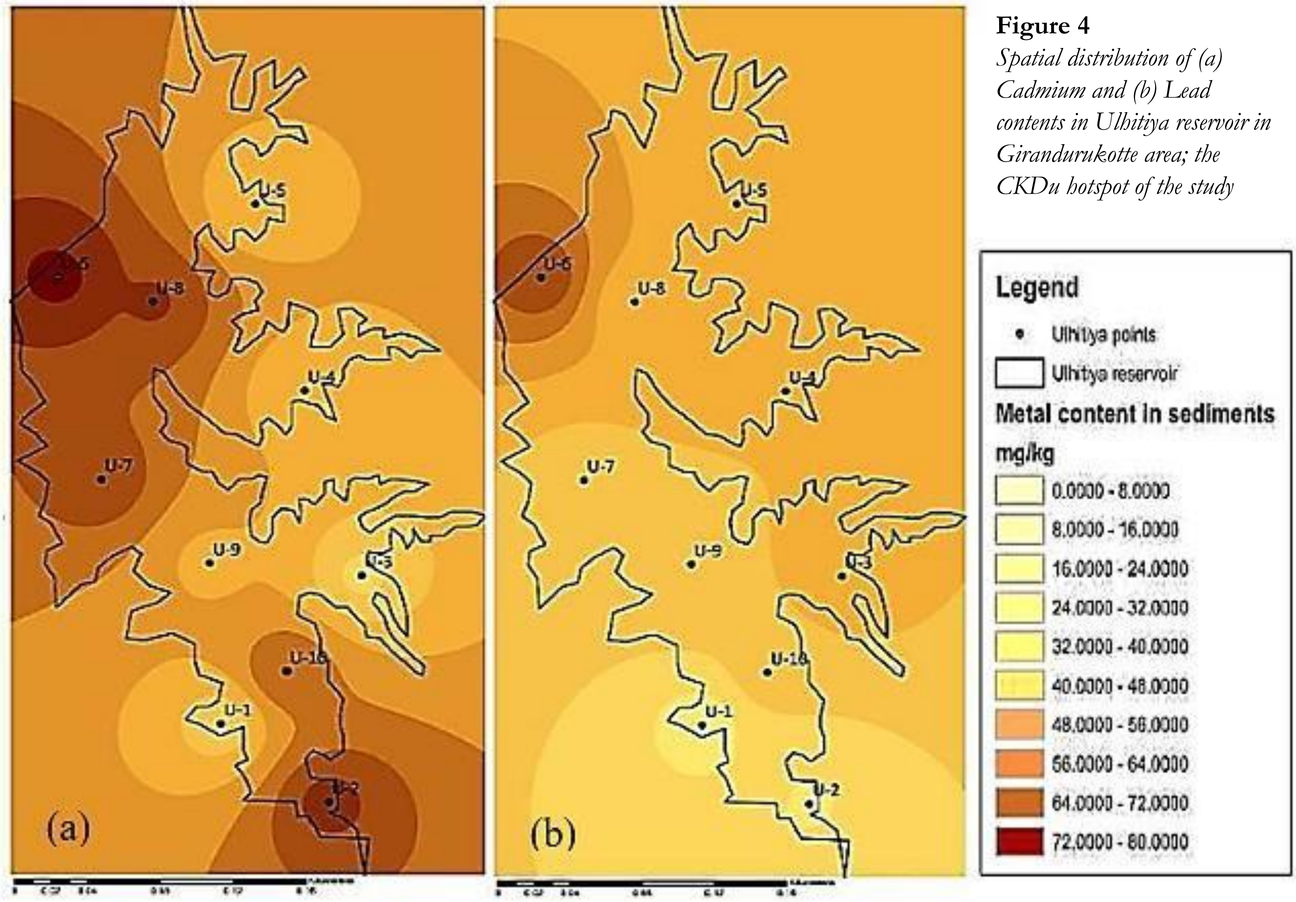

Figure 4
Spatial distribution of (a) Cadmium and (b) Lead contents in Ulhitiya reservoir in Girandurukotte area; the CKDu hotspot of the study

resulting in high accumulations of heavy metals in sediments. These can be the reasons associated with the low levels of Cd and Pb in Ulhitiya sediments. These interactions can complicate heavy metal transport and increase the ecological risk of secondary pollution. Consequently, it is crucial to analyze bottom deposits from reservoirs for heavy metals to support environmental management, particularly for sediments from drinking water reservoirs. Therefore, it is vital to investigate heavy metal pollution and assess the associated pollution sources and ecological risks from reservoir sediments. Spatial autocorrelation analysis revealed distinct distributional patterns of heavy metals across the study area, reflecting both natural geochemical processes and anthropogenic influences. The spatial pattern of Cd demonstrated a tendency to cluster within paddy cultivation zones, indicating a strong association between Cd accumulation and agricultural practices. This clustering suggests that Cd enrichment in soils may result from repeated agrochemical inputs, such as fertilizers and pesticides, that inadvertently introduce Cd as a contaminant. In contrast, Moran's Index values for Pb, As, and Cr indicated a random or evenly distributed spatial pattern across the landscape. Such uniformity may be attributed to geogenic mineral composition, irrigation with contaminated reservoir water, or aerosol-mediated deposition of particulate-bound metals, all of which contribute to a diffuse background distribution rather than localized hotspots. The observed heavy metal/metalloid contamination in soils poses significant ecological and public health implications. Exposure pathways include direct ingestion or dermal contact with contaminated soils, uptake through the soil–plant–human and soil–plant–animal–human food chains, and consumption of polluted groundwater (Ling et al., 2007; McLaughlin et al., 2000). Moreover, elevated soil metal concentrations can lead to phytotoxicity, thereby reducing crop yield, nutritional quality, and marketability, while indirectly compromising food safety. Long-term human exposure to trace concentrations of toxic metals through multiple pathways may lead to bioaccumulation, which can adversely affect renal physiology and contribute to the development of chronic non-communicable diseases, notably chronic kidney disease of uncertain etiology (CKDu) in rural a-

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gricultural populations. Agriculture, particularly paddy cultivation, exerts a major anthropogenic influence on soil geochemistry within the study region. Paddy crops require adequate levels of macronutrients (N, P, K, S, Ca, and Mg) and micronutrients, including Cu and Zn, for optimal growth. In many tropical soils deficient in these essential elements, micronutrient-enriched fertilizers are commonly applied (Arao and Ae, 2003). However, commercial fertilizers—especially phosphate-based fertilizers—often contain trace impurities of toxic metals such as Cd and Pb (Maslin and Maier, 2000). Continuous use of such fertilizers can lead to a progressive buildup of these elements in agricultural soils over time. Moreover, the use of certain phosphatic fertilizers inadvertently increases soil concentrations of Cd and Pb, as well as other potentially hazardous metals (Karatas et al., 2007). Additional sources of metal dispersion include industrial and thermal processes, during which metals such as As and Pb may volatilize at elevated temperatures and subsequently condense as fine particulate oxides, particularly under oxidizing atmospheric conditions (USEPA, 2002). These particulates can undergo long-range atmospheric transport, contributing to the spatially uniform deposition of As and Pb observed in the study. Such atmospheric redistribution mechanisms may, therefore, explain the evenly distributed spatial patterns of these metals, contrasting with the localized Cd clustering associated with agricultural fields. Although the precise etiology of CKDu remains unresolved, the current findings support the hypothesis of a multifactorial origin involving environmental nephrotoxicants, occupationnal exposure, and socio-ecological determinants. Agricultural workers in CKDu-endemic areas may experience chronic low-dose exposure to metal mixtures through contaminated soil, water, and food, resulting in cumulative renal toxicity over time. Understanding the chemical speciation, environmental behavior, and bioavailability of these metals is essential for identifying their toxic potential and for developing effective remediation and mitigation strategies. The fate and mobility of heavy metals in soils are governed primarily by their chemical form and speciation (McLaughlin et al., 2000). Metals incorporated into silicate minerals typically represent the geogenic background fraction, posing limited environmental risk, whereas those present as exchangeable ions, carbonate- or phosphate-bound forms, or organometallic complexes are more labile and bioavailable. Metals associated with soil organic matter or adsorbed onto mineral surfaces can participate in ion-exchange reactions, influencing their migration to groundwater and plant uptake. Hence, evaluating the speciation profiles of metals in CKDu-prone soils is critical for understanding exposure risk, toxicity mechanisms, and the persistence of contamination in the affected ecosystems. This investigation provides crucial insight into the geo-environmental dynamics of nephrotoxic elements within CKDu-endemic regions. The integration of spatial autocorrelation analysis, soil geochemistry, and land-use characterization underscores the complex interactions between agricultural practices, natural soil processes, and human health outcomes. The findings highlight that Cd accumulation in paddy fields is closely linked to agrochemical usage, while As and Pb dispersion likely arises from geogenic and atmospheric processes. Understanding these spatial and mechanistic patterns is fundamental to developing evidence-based soil management frameworks, reducing human exposure risks, and supporting policy interventions aimed at mitigating CKDu prevalence among vulnerable rural farming communities.

Conclusions

Heavy metal contamination in agricultural soils has become a major environmental and public health concern due to its persistence, ecological risk, and nephrotoxic potential. In the present study, elevated heavy metal levels were identified as a possible contributing factor to CKDu prevalence in the investigated region. The abundance order of heavy metals in soils from the CKDu-endemic area was Zn > Cu > Pb > As > Cr > Cd, with Cd, Pb, and Cr significantly higher than in the non-endemic reference site. Although most metals were below the maximum permissible concentrations (MPCs), As and Zn exceeded the limits, suggesting possible environmental and health hazards. Spatial autocorrelation analysis revealed that Cd exhibited a clustered spatial pattern (MI = 0.3145), particularly concentrated in paddy-cultivated zones, while Pb, As, and Cr were randomly distributed (MIs = –0.0737, –0.0316, and –0.8072). The Cd clustering pattern indicates a strong link between agricultural activities and soil contamination, likely arising from the repeated use of phosphate fertilizers containing trace Cd and Pb impurities. The accumulation of Cd, Pb, As, and Cr in agricultural soils and their potential uptake by rice plants highlight a critical exposure pathway through the soil–plant–human continuum, posing long-term risks for CKDu development. Therefore, controlling agrochemical pollution sources and promoting sustainable fertilizer management are imperative. This study provi-

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des an early-warning basis for environmental nephron-toxicity assessment and supports policy formulation for effective agricultural soil pollution control in CKDu-affected regions of Sri Lanka.

References

ADRIANO D.C. (2001) Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability and Risks of Metals, 2nd Edition, Springer, New York, 867.

http://dx.doi.org/10.1007/978-0-387-21510-5.

ARAO T., ISHIKAWA S., MURAKAMI M., ABE K., MAEJIMA Y., MAKINO T. (2010) Heavy metal contamination of agricultural soil and countermeasures in Japan, Paddy and Water Environment, 8(3):247–257.

https://doi.org/10.1007/s10333-010-0205-7

ARAO T., AE N. (2003) Genotypic variations in cadmium levels of rice grain, Soil Science and Plant Nutrition, 49(4), 473–479. ttps://doi.org/10.1080/00380768.2003.10410035

BREVIK E.C., CERDÀ A., MATAIX-SOLERA J., PEREG L., QUINTON J.N., SIX J., VAN OOST K. (2015) The interdisciplinary nature of Soil- Soil, 1: 117–129. https://doi.org/10.5194/soil-1-117-2015

BREVIK E.C., BURGESS L.C. (2012) Soils and human health, CRC Press, Boca Raton, FL, 408.

KABATA-PENDIAS A. (2001) Trace Elements in Soils and Plants, CRC Press, Boca Raton, Fla, USA.

KARATAS M., DURSUN S., GULER E., OZDEMIR C., EMIN M.A. (2007) Heavy metal accumulation in wheat plants irrigated by waste water, Cellulose Chemistry and Technology, 40(7):575–579.

LING W., SHEN Q., GAO Y., GU X., YANG Z. (2007) Use of bentonite to control the release of copper from contaminated soils, Australian Journal of Soil Research, 45(8):618–623. https://doi.org/10.1071/SR07079

LIU J.G., LIANG J.S., LI K.Q. (2003) Correlations between cadmium and mineral nutrients in absorption and accumulation in various genotypes of rice under cadmium stress, Chemosphere, 52(9):1467–1473. https://doi.org/10.1016/S0045-6535(03)00484-3

MASLIN P., MAIER R.M. (2000) Rhamnolipid-enhanced mineralization of phenanthrene in organic-metal co-contaminated soils, Bioremediation Journal, 4(4): 295–308. https://doi.org/10.1080/10889860091114266

MCLAUGHLIN, M. J., ZARCINAS, B. A., STEVENS, D. P., COOK, N. (2000) Soil testing for heavy metals, Communications in Soil Science and Plant Analysis. 31(11–14): 1661–1700. https://doi.org/10.1080/00103620009370531

MCLAUGHLIN M.J., HAMON R.E., MCLAREN R.G., SPEIR T.W., ROGERS S.L. (2000) Review: a bioavailability-based rationale for controlling metal and metalloid contamination of agricultural land in Australia and New Zealand", Australian Journal of Soil Research, 38(6): 1037–1086. https://doi.org/10.1071/SR99128

ROBINSON D.A., FRASER I., DOMINATI E.J., DAVÍDSDOTTIR B., JÓNSSON J.O.G., JONES L., JONES S.B., TULLER M., LEBRON I., BRISTOW K.L., SOUZA D.M., BANWART S., CLOTHIER B. (2014) On the Value of soil resources in the context of natural capital and ecosystem service delivery. Soil Science Society American Journal. 78: 685–700. https://doi.org/10.2136/sssaj2014.01.0017

US Environmental Protection Agency (USEPA), Region 9, Preliminary Remediation Goals, USEPA, Washington, DC, USA, 2002.

WANG Y., LUO T.M.Z. (2012) Geostatistical and geochemical analysis of surface water leakage into groundwater on a regional scale: a case study in the Liulin karst system, northwestern China, J Hydrol. 246:223–234. https://doi.org/10.1016/S0022-1694(01)00376-6