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EDITED BY

Jingzi Beiyuan,
Foshan University, China

REVIEWED BY

Xiaoming Wan,
Institute of Geographic Sciences and Natural
Resources Research, China
Srimathie Indraratne,
University of Winnipeg, Canada

*CORRESPONDENCE

Geomar Vallejos-Torres
✉ gvallejos@unsm.edu.pe

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Cadmium distribution and soil properties across soil orders under cacao (*Theobroma cacao* L.) cultivation in the Peruvian Amazon

Geomar Vallejos-Torres^{1,2*}, Rodolfo J. Chuchon-Remon¹,
Nery Gaona-Jimenez², Juancarlos Cruz-Luis³
and Richard Solórzano-Acosta³

¹Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Estación Experimental Agraria El Porvenir, Juan Guerra, Peru, ²Facultad de Ciencias Agrarias, Universidad Nacional de San Martín, Tarapoto, Peru, ³Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Lima, Peru

Introduction: High cadmium (Cd) levels in Peru are limiting access to international markets that have implemented stricter thresholds for allowable concentrations in chocolate and its derivatives. This study aimed to analyse the distribution of cadmium profiles and their edaphic controls across different soil orders under cacao (*Theobroma cacao* L.) cultivation in the Peruvian Amazon.

Methods: The research was conducted in three locations within two districts of the San Martín department, encompassing an area of 4,073.54 km². The study sites included the towns of La Unión and Nuevo San Martín in the Pólvora district (Tocache province) and the town of Perla Mayo in the Campanilla district (Mariscal Cáceres province). In each locality, ten 100 m² plots were selected, resulting in a total of 30 plots. Soil samples were collected by excavating pits measuring 1 × 0.8 m, with samples taken from two depth intervals: 0–30 cm and 30–60 cm.

Results: Total cadmium concentrations and key physicochemical parameters were then analysed. The soils in La Unión exhibited the highest average Cd concentrations at 0–30 cm depth (1.35 ± 0.21 mg/kg), while the lowest concentrations were recorded in Perla Mayo at the same depth (0.27 ± 0.25 mg/kg). Regarding soil classification, Entisols and Alfisols presented the lowest average Cd contents (0.66 ± 0.35 mg/kg and 0.15 ± 0.15 mg/kg, respectively). Among the evaluated soil properties, cation exchange capacity (CEC) and clay content were identified as the primary factors influencing cadmium levels, followed by soil pH.

Discussion: The cadmium tends to accumulate in the surface horizons of fine-textured, acidic soils at each study site. The edaphic conditions in Perla Mayo appear to be the most favourable, showing minimal cadmium accumulation, and may serve as a reference for developing agricultural management strategies aimed at reducing cadmium uptake in cacao-growing soils.

KEYWORDS

cadmium distribution, physicochemical properties, cacao, soil orders, cation exchange capacity, Peruvian Amazon, heavy metal, geostatistical analysis

1 Introduction

Peru is the eighth-largest producer of cocoa beans worldwide; however, high cadmium (Cd) levels are restricting access to international markets, which have established upper thresholds for allowable concentrations in chocolate and its derivatives (1). Cd is one of the most important toxic environmental of heavy metals. Cd pollutes the environment mainly from mining, metallurgy industry, pigments and plastic stabilizers, and manufactures of nickel–cadmium batteries. Some important human intoxication sources are food, water, cigarette smoke, and air contamination (2). Soil and water contamination by Cd is a well-known issue that has recently gained renewed concern. Cadmium toxicity causes multiple forms of damage to plants, affecting them from the germination stage through yield suppression. Key physiological functions—such as water relations, essential mineral uptake, and photosynthesis—are also impaired by Cd exposure (3). It also disrupts key physiological processes, including water interactions, uptake of essential nutrients, and photosynthesis (3). Beyond plant systems, elevated Cd levels pose serious risks to human and animal health due to this toxic metal's persistence and bioaccumulation in the environment (4). Industrial activities, such as mining, metal smelting, and the use of wastewater for irrigation, have contributed to widespread heavy metal contamination of soil, making it one of the most pressing global environmental issues (5). As a result, Cd is recognized as a highly toxic heavy metal that can remain in soils for extended periods. Nevertheless, its dynamics in the soil are regulated by a range of beneficial soil constituents and chemical processes, which may help mitigate its adverse effects (6).

Anthropogenic activities are a major source of Cd contamination; in addition, the PCA revealed that Cd also originates mainly from anthropogenic sources in both leaf and soil samples (7). Cadmium may occur naturally in the Earth's crust or derive from human activities (8). Compared with other heavy metals, Cd is highly soluble and exhibits greater mobility, making it readily absorbed by plants (9). Once taken up, Cd is translocated and accumulates in the edible parts of plants (10). Once absorbed, Cd is translocated within the plant and tends to accumulate in edible tissues (10), posing a serious health risk. It is considered one of the most toxic and hazardous heavy metals to living organisms (11, 12) due to its high toxicity and strong bioaccumulation potential (13, 14). Soil plays a fundamental role in human survival and development, acting not only as the foundation of terrestrial ecosystems but also as a critical sink for toxic metal contaminants. This is attributed to its natural capacity to retain, filter, and buffer pollutants (15). Consequently, soil contamination by toxic metals has drawn increasing academic and public concern worldwide over recent decades (16, 17).

The cacao plant (*Theobroma cacao* L.), native to South America, holds vital economic and social importance for millions of smallholder farmers across tropical countries, including Peru (18). Global demand for cocoa beans has increased steadily, with imports growing at an average annual rate of 6.3%, reaching cumulative

growth rates of up to 189% in recent years (19). In Peru, the San Martín region alone contributes approximately 38% of the nation's total cocoa production (20). However, recent studies have shown that cacao plants can absorb and translocate heavy metals from the soil into their vegetative tissues, often resulting in concentrations that exceed the maximum permissible limits (21). Although Peru ranks as the eighth largest cocoa producer worldwide, elevated Cd levels in some production regions are hindering access to international markets that have implemented strict maximum thresholds for allowable concentrations in chocolate and its derivatives.

In the San Martín region, cocoa cultivation is commonly practiced as a monoculture or in association with shade trees, which supports the conservation of beneficial soil microorganisms, such as arbuscular mycorrhizal fungi, that promote the healthy development of cocoa cultivation (22). Studies have shown that monoculture systems in the San Martín region tend to accumulate higher Cd concentrations in both leaves and beans compared to agroforestry systems. As a result, cocoa cultivated under agroforestry conditions generally exhibits lower overall Cd levels compared to monoculture systems. However, the elevated cadmium concentrations detected in leaves and beans under monoculture systems frequently exceed the maximum permissible limits established by the World Health Organization (WHO), raising concern among cocoa-producing communities in several regions of Peru, such as Ucayali and Amazonas. Variations in the underlying geology and soil mineralogy can act as sources of Cd-bearing sediments. Furthermore, Cd levels in cocoa plants result from a combined mechanism involving plant bioaccumulation and the high Cd content of fertilizers, with a smaller contribution from Cd-bearing minerals present in alluvial soil sediments (23). Meanwhile, cocoa ecosystems associated with shade tree species may represent a promising strategy for Cd phytoextraction, potentially reducing the metal's bioavailability and accumulation in cocoa beans (24).

In the present study, the distribution of cadmium in soils from different cocoa-producing localities within the San Martín region was previously unknown. Therefore, this study provides a detailed assessment of cadmium distribution and soil properties across soil orders under cocoa cultivation in the Peruvian Amazon. This new knowledge will have a significant impact on cocoa development and traceability, as it will help prevent the establishment of new plantations in areas close to the maximum permissible limits of soil Cd content. Consequently, this could also influence the cadmium concentration in cocoa beans. Cocoa plantations in Peru show wide variability in Cd content in beans, with average concentrations ranging from 0.076 to 0.99 mg/kg, as reported by Mendoza-López et al. (25) Rosales-Huamán et al. (26), and Oliva et al. (21). Therefore, this study aimed to analyze the distribution of cadmium profiles and their edaphic controls across different soil orders under cocoa (*Theobroma cacao* L.) cultivation in the Peruvian Amazon. The working hypothesis was that geographic location exerts a strong influence on Cd levels, followed by soil texture, and to a lesser extent, soil order.

2 Materials and methods

2.1 Study area

The study was conducted between May and December 2024 in three locations within the San Martín department, which spans an area of 51,253.31 km² and is characterized by a predominantly subtropical and tropical climate, with two distinct seasons: a dry season from June to September and a rainy season from October to May. Temperatures range from 23 to 27 °C, and the average annual rainfall is approximately 1,500 mm. The three study sites are located within this region: Perla Mayo, situated in the Campanilla district of the Mariscal Cáceres province, and La Unión and Nuevo San Martín, both located in the Polvora district of the Tocache province. Campanilla is situated in the Amazonian foothills, on terraces and hillsides, with predominantly gentle and undulating slopes (8–20%), whereas Polvora is characterized by steeper terrain, featuring high hills and slopes ranging from 35% to 60% (27), as shown in Figure 1.

2.2 Sampling design

For this study, ten plots of 100 m² (10 m × 10 m) were selected in each locality, resulting in a total of 30 plots. The selection was carried out following the methodology described by Yu et al. (28) (Figure 1). Soil sampling was conducted by digging 1 × 0.8 × 1 m pits. Before digging the holes, each site was cleared of weeds and leaf litter. Samples were collected using a shovel and a metal bar. At each plot, one soil sample was taken from each of two depth intervals: 0–30 cm and 30–60 cm. These depths were selected based on previous studies that reported significant variations in Cd concentrations at similar soil profiles (29–31). A total of 60 soil samples were collected from the two depths for cadmium and physicochemical property analyses.

2.3 Calculation of soil edaphic and nutritional parameters

Samples were analyzed at the accredited laboratory of the National Institute of Agrarian Innovation (INIA), Peru. Soil

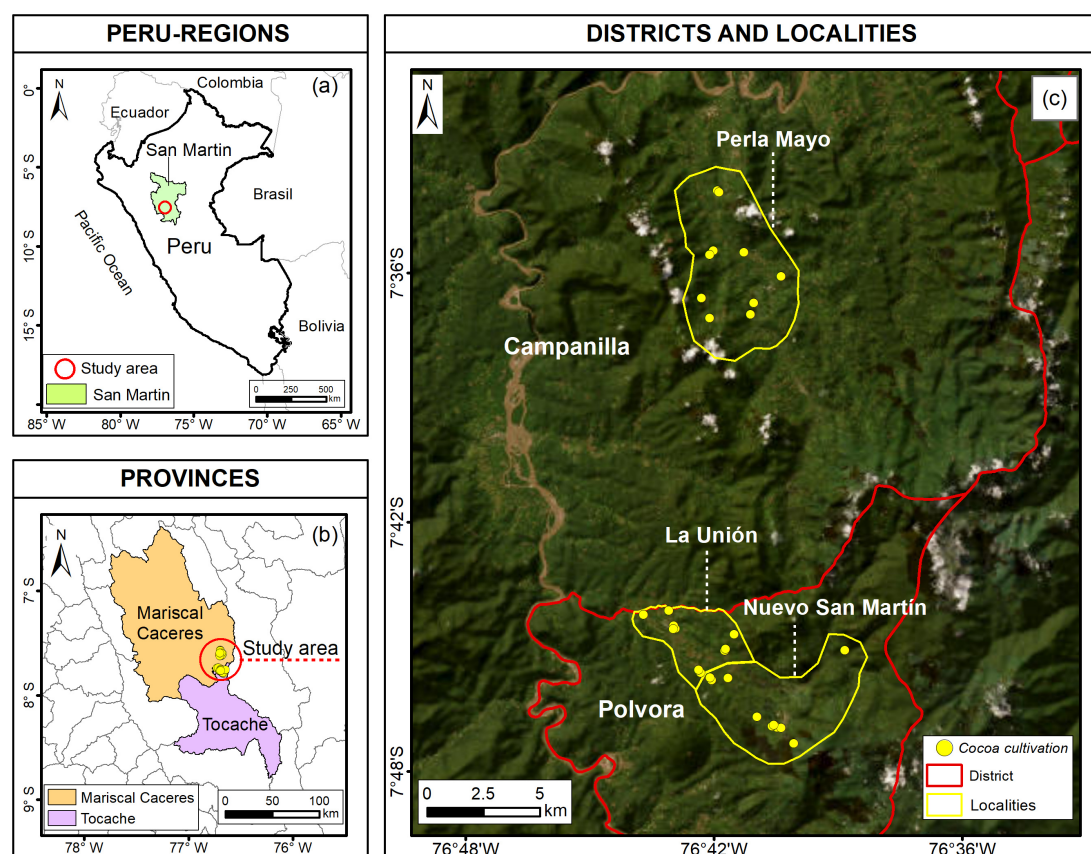


FIGURE 1

Location of the study area in San Martín, Peru: (A) Country and region; (B) Provincial boundaries; (C) District boundaries, localities, and sampling points.

texture was determined using the hydrometer method. Soil pH was measured potentiometrically in a 1:2.5 soil-to-water suspension, and soil organic matter (SOM) was determined according to the NOM-021-RECNAT-2000 method (2002) (32). Total nitrogen was quantified using the Kjeldahl method (33), available phosphorus following the Olsen and Sommers (34) method, and available potassium according to NOM-021-RECNAT-2000 (32). The same method was employed to determine ECEC, EC, Ca, and Mg. For the characterization of soil orders, the study involved a soil specialist from the National University of San Martín and the National Institute of Agricultural Innovation, who identified the three soil orders based on horizon profiles, color, and soil characteristics of each plot. Additionally, the thematic studies for the Ecological and Economic Zoning of the San Martín Department conducted by Escobedo (35) were used as a reference.

2.4 Determination of total cadmium in soils

For total cadmium analysis, one soil sample per subplot was collected following the Technical Sampling Guide developed by the Peruvian Ministry of the Environment (36). Total cadmium in soil was determined using the EPA 3051A method (37), which employs microwave-assisted acid digestion with nitric acid (HNO_3) to simulate conventional heating-based extraction. Soil pH was measured potentiometrically (InLab Expert Pro-ISM, Mettler Toledo, Australia) in a 1:2.5 soil-to-water suspension, following the Davey and Conyers (38) method, at a rate of 10 g of soil in 25 mL of water (1:2.5).

The Cd analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS), following the quality assurance and quality control (QA/QC) procedures established in the US EPA methods (39) and US EPA (40). Each analytical batch included a method blank to check for potential contamination, a fortified duplicate sample (5%) to assess precision and bias, and a laboratory control sample (LCS) with known concentrations to verify accuracy. Analytical performance was validated using standard reference materials (SRMs) from NIST, ensuring the reliability and traceability of the results.

2.5 Statistical and geostatistical analyses

All statistical analyses were conducted using R software (version 4.4.0; 41), primarily employing the FactoMineR, factoextra, ggplot2, and corrplot packages. Firstly, soil physicochemical variables, including pH, effective cation exchange capacity (CEC), organic matter (OM), exchangeable K, Ca, Mg, Al, acidity, cadmium, and texture components, were standardized to a z-scale to ensure equal weighting across variables. Principal Component Analysis (PCA) was performed across different depth strata (0–30 cm and 30–60 cm), texture classes, soil orders, and sampling locations to identify clusters and spatial variability patterns in soil properties. Thirteen physicochemical attributes of the soil (pH, electrical conductivity [EC], CEC, OM, exchangeable K, Al, Ca, Mg, acidity, Cd, sand,

clay, and sampling depth) were screened for outliers and standardized to z-scale (centred and scaled) before multivariate analysis, ensuring that all variables contributed comparably to the total variance. Categorical variables, including depth (0–30 cm and 30–60 cm), the three locations, and classifications of soil texture and order, were coded as factors. The assumptions of normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. When necessary, $\log_{10}$ transformations were applied to meet analysis of variance (ANOVA) assumptions. The Kaiser–Meyer–Olkin (KMO) eigenratios (> 0.75) confirmed the adequacy of the data for PCA. ANOVA was performed for each variable, followed by Tukey's Honest Significant Difference (HSD) test to compare means among locations within each depth interval.

The geostatistical analysis was carried out using the SmartMap plugin in QGIS software version 3.34.14 (Prizren), applying the ordinary kriging method (42, 43). This method allows modeling the spatial continuity of soil properties based on the structure of dependence among point observations (44). The process began with the construction of the experimental semivariogram from the sampled data, followed by fitting the theoretical model (spherical, exponential, or Gaussian) that best represented the spatial variability. From this model, the nugget (C_0), sill ($C_0 + C_1$), and range (a) parameters were estimated, describing the magnitude and extent of the spatial autocorrelation of the variable. Subsequently, ordinary kriging was applied to generate continuous maps of estimated values and associated errors, ensuring a precise and coherent cartographic representation. Cross-validation was performed to evaluate model performance using RMSE and R^2 indicators, thereby ensuring the reliability and consistency of the spatial predictions (45).

3 Results

3.1 Principal component analysis of soil physicochemical parameters associated with total cadmium across locations and soil profiles

Mean Cd concentrations differed significantly among locations (ANOVA, $p < 0.0001$ with the highest values observed in La Unión (1.35 ± 0.21 mg/kg), intermediate values in Nuevo San Martín (0.78 ± 0.30 mg/kg) and the lowest in Perla Mayo (0.27 ± 0.25 mg/kg) at 0–30 cm soil depth (Table 1, Figure 2A). A similar pattern was observed from 30–60 cm depth. At both depths, cadmium exhibited the highest F-values ($F = 50.4$ and 46.5 ; $p < 0.0001$), consistently following the concentration pattern La Unión $>$ Nuevo San Martín $>$ Perla Mayo (grouped as letters a–c). These results align with the 'fertility–texture' axis identified in the PCA, where CEC, K, and Ca showed strong positive loadings, and Cd and sand contributed negatively. This axis is reflected in the mean differences among sites: Perla Mayo, characterized by higher pH (5.76–5.86) and Ca (~ 11 mg/kg), exhibited the lowest Cd concentrations (0.27–0.28 mg/kg). In contrast, La Unión, acidic and base-poor, recorded the highest Cd levels (1.35–1.29 mg/kg), supporting the observed

TABLE 1 Analysis of variance and Tukey test of the physicochemical soil parameters associated with cadmium across locations and soil profiles.

Physicochemical parameters	Soil depth (cm)	Tukey test by locations			Analysis of variance	
		La Union	Nuevo San Martin	Perla Mayo	F	P-value
pH	0-30	4.65 ± 0.21 b	5.13 ± 0.16 ab	5.76 ± 0.25 a	4.94	0.0195*
	30-60	4.49 ± 0.19 b	5.12 ± 0.51 ab	5.86 ± 1.12 a	7.04	0.0055***
EC (dS/cm)	0-30	10.49 ± 3.13 a	3.32 ± 2.86 b	11.46 ± 5.65 a	9.86	0.0013***
	30-60	4.58 ± 2.82 a	4.15 ± 4.77 a	6.14 ± 3.89 a	0.54	0.592
OM (%)	0-30	2.42 ± 0.75 a	1.21 ± 0.53 b	2.6 ± 0.90 a	9.16	0.0018***
	30-60	1.08 ± 0.42 a	1.2 ± 0.79 a	1.81 ± 0.63 a	3.39	0.056
K (mg/kg)	0-30	46.27 ± 10.88 b	47.82 ± 16.73 b	83.08 ± 29.35 a	7.43	0.0044***
	30-60	39.6 ± 23.32 b	45.51 ± 13.33 ab	73.63 ± 27.53 a	5.36	0.0149*
CECe (cmol/kg)	0-30	4.61 ± 2.05 b	4.56 ± 1.07 b	13.91 ± 6.65 a	15.40	<0.0001***
	30-60	2.78 ± 1.06 b	4.45 ± 1.12 b	13.79 ± 6.04 a	25.90	<0.0001***
Cd (mg/kg)	0-30	1.35 ± 0.21 a	0.81 ± 0.16 b	0.27 ± 0.25 c	50.40	<0.0001***
	30-60	1.29 ± 0.19 a	0.91 ± 0.14 b	0.28 ± 0.28 c	46.50	<0.0001***
Sand (%)	0-30	53.47 ± 9.96 a	48.23 ± 8.60 a	49.71 ± 8.69 a	1.94	0.172
	30-60	55.86 ± 8.18 a	49.8 ± 8.81 a	48.39 ± 7.25 a	2.30	0.129
Clay (%)	0-30	18.25 ± 7.09 b	23.48 ± 4.38 ab	25.08 ± 4.23 a	3.89	0.0396*
	30-60	18.52 ± 2.86 b	24.07 ± 5.52 a	27.01 ± 5.92 a	7.93	0.0034***
Acidity	0-30	0.75 ± 0.77 a	1.38 ± 1.21 a	0.9 ± 1.46 a	0.69	0.516
	30-60	1.04 ± 0.75 a	1.53 ± 1.45 a	1.66 ± 1.46 a	0.49	0.622
Al (cmol (+)/Kg)	0-30	0.00 ± 0.00 a	0.48 ± 0.76 a	0.08 ± 0.18 a	2.94	0.079
	30-60	0.02 ± 0.06 a	0.54 ± 0.93 a	0.16 ± 0.21 a	2.26	0.134
Ca (cmol (+)/Kg)	0-30	2.85 ± 1.86 b	2.23 ± 1.79 b	11.49 ± 6.90 a	13.20	0.0003***
	30-60	1.25 ± 0.93 b	1.93 ± 1.61 b	11.13 ± 6.79 a	16.70	<0.0001***
Mg (cmol (+)/kg)	0-30	0.69 ± 0.52 ab	0.49 ± 0.41 b	1.09 ± 0.62 a	3.72	0.0445*
	30-60	0.27 ± 0.27 b	0.55 ± 0.41 ab	0.95 ± 0.54 a	7.50	0.0043***

Different letters within each physicochemical parameter indicate statistically significant differences among locations at $p < 0.05$, as determined by Tukey's test. ns: not significant; *statistically significant; ***highly statistically significant.

negative Cd–pH and positive Cd–acidity correlations (Table 1). Soil texture further supports this interpretation. Clay content increased significantly in Perla Mayo ($p < 0.01$ at depth), consistent with greater Cd retention, as reflected in deeper-layer correlation matrices. Sand content did not statistically differ among sites, suggesting that its contribution to PC1 represents a directional trend rather than a significant difference in means. The loss of significance for some variables (surface OM, EC, and subsoil Al) is consistent with their lower factor loadings or intermediate uniqueness in the PCA, indicating a reduced contribution to total variance and, therefore, insufficient inter-site variation to reach statistical thresholds. In summary, the ANOVA and Tukey test results not only corroborate but also quantify the site and depth-related patterns revealed by the PCA and correlation analyses. Cadmium clearly emerges as the most discriminating variable, validated by both its high F-values and PCA loadings/uniqueness

scores, while chemical-related properties define the contrasting fertility environment that modulates its distribution. These findings confirm the overall coherence and robustness of the multivariate approach.

In PCAs (Figures 2A, B), the variance structure remained remarkably consistent: axis 1 accounted for approximately 43% of the total variance (43.2% and 43.3%, respectively), while axis 2 increased the cumulative variance to 60.6% and 63.5%. This stability indicates that, regardless of soil depth, the same edaphic gradients drive the differences among the three locations. Vector analysis confirms that the first principal component is primarily influenced by fertility-related variables (CECe, K, Ca), which exhibit strong positive loadings, whereas textural variables such as sand display negative loadings. This configuration forms a “fertility–texture” axis in which cadmium plays a minimal role; Cd presents only weak negative loadings on PC1 (−0.20, −0.33, −0.26) and moderate

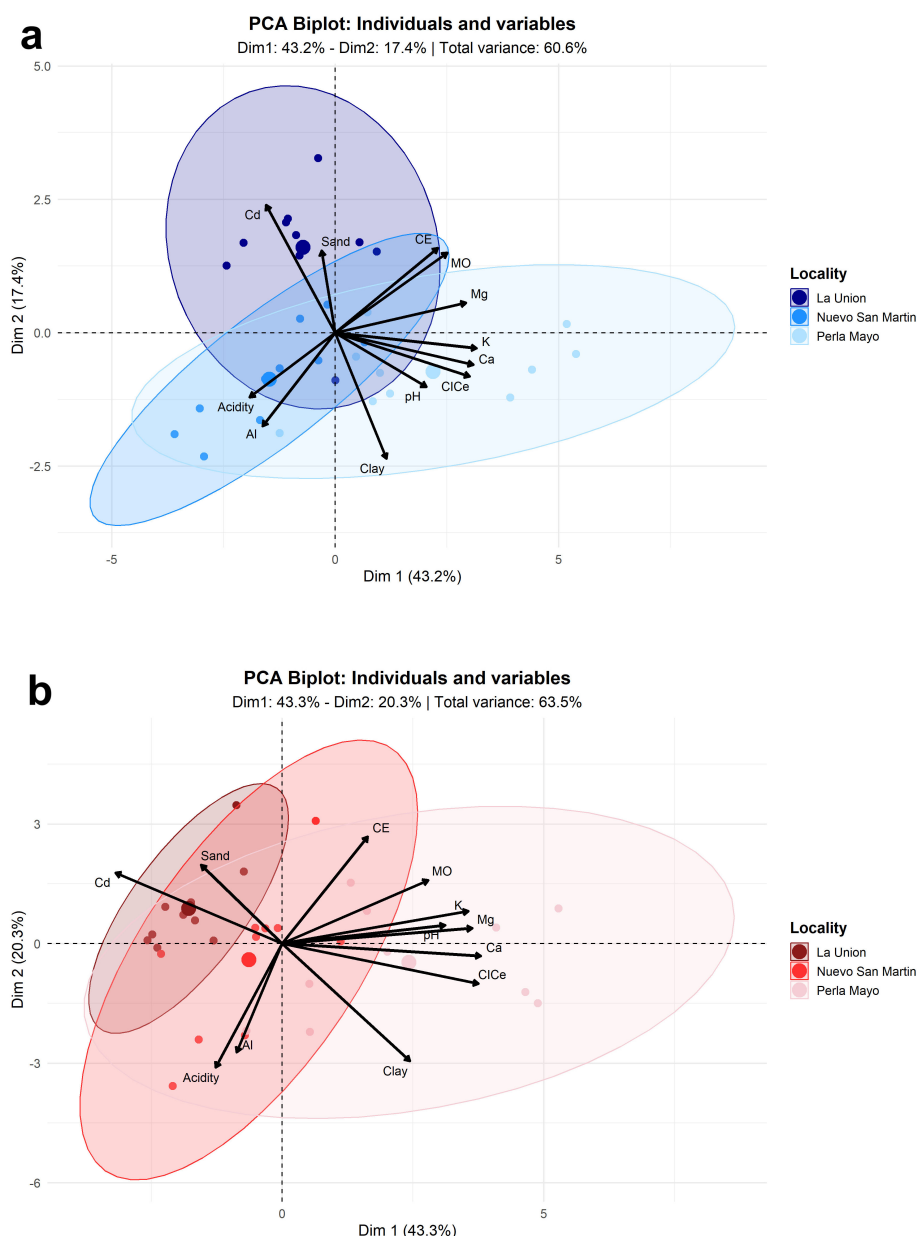


FIGURE 2

PCA at a depth of 0–30 cm (A) and 30–60 cm (B) of physicochemical soil parameters associated with cadmium across locations and soil profiles.

positive loadings on PC2 (0.47, 0.27, 0.38), suggesting that the second component reflects a heavy metal gradient superimposed on underlying gradients of acidity and texture. The uniqueness index supports this interpretation: Cd displays partial unique variance (0.64) in the surface layer, increasing to 0.80 at 30–60 cm Depth, indicating that its distribution depends on both site-specific processes and the broader edaphic gradients captured by the PCA. Together, the figures reveal apparent clustering of locations, with PC1 separating them based on fertility and texture, and PC2 based on Cd levels, thus confirming that the method effectively addresses the proposed hypothesis. Cadmium emerges as a secondary but consistent explanatory variable that distinguishes soil depths within each location, while also covarying with acidity

and base saturation, validating the use of PCA as an effective tool for interpreting the influence of Cd across soil profiles in the three study sites.

3.2 Principal component analysis of physicochemical soil parameters associated with total cadmium across soil orders and profiles

Statistically significant differences ($p < 0.05$) between soil orders were observed for pH, effective cation exchange capacity (CEC), cadmium (Cd) content, clay, calcium (Ca), and magnesium (Mg)

(Table 2). Soil pH was significantly lower in Inceptisols at both depths, a condition that may enhance Cd mobility and availability. Correspondingly, Cd concentrations were highest in Inceptisols, followed by Alfisols, and lowest in Entisols, consistent with the patterns observed in Table 3. CECe values were also lower in Inceptisols, suggesting a reduced capacity to retain cations such as Cd. In contrast, Entisols exhibited significantly higher clay content, which may contribute to greater heavy metal retention and justify the lower Cd levels in these soils. Similarly, Ca and Mg concentrations were lower in Inceptisols, potentially impacting their fertility status in soils. Collectively, these findings underscore the importance of soil type in cadmium dynamics. Entisols appear to offer more favorable conditions for limiting Cd accumulation, likely due to their higher pH and clay content, whereas Inceptisols are more susceptible, owing to their lower pH, reduced CECe, and elevated Cd concentrations.

At both depths (0–30 cm and 30–60 cm; Figures 3A, B), the first principal component (PC1) explains between 42.5% and 43.3% of the variance, while the second component (PC2) increases the cumulative explained variance to over 60%. The orientation of the vectors in the biplots suggests that PC1 is predominantly influenced by fertility-related variables such as CECe, K, and Ca, all of which have high positive loadings. In contrast, variables like sand content and acidity are clustered at the opposite end of the axis, forming a gradient that reflects fertility, texture, and acidity. Cadmium (Cd), meanwhile, exhibits a more pronounced behavior along PC2, with moderate loadings (ranging from 0.26 to 0.47) and uniqueness values between 0.64 and 0.80. Overall, the soil order PCAs indicate that cadmium distribution is influenced by both soil acidity and cation exchange capacity. While its behavior varies slightly with depth and model structure, Cd consistently emerges as a secondary but consistent variable. This supports its inclusion in the analysis

TABLE 2 Analysis of variance and Tukey's test of the soil physicochemical parameters associated with cadmium in soil orders and profiles.

Physicochemical parameters	Soil depth (cm)	Tukey test by location			Analysis of variance	
		Inceptisol	Alfisol	Entisol	F	P-value
pH	0-30	4.68 ± 0.21 b	5.61 ± 0.16 ab	6.2 ± 0.25 a	7.31	0.0029***
	30-60	4.6 ± 0.19 b	5.62 ± 0.51 ab	6.35 ± 1.12 a	8.75	0.0012***
EC (dS/cm)	0-30	9.63 ± 3.13 a	7.43 ± 1.56 a	5.85 ± 1.65 a	1.65	0.211
	30-60	3.99 ± 1.22 a	6.22 ± 2.65 a	3.95 ± 1.79 a	0.62	0.544
OM (%)	0-30	2.16 ± 0.35 a	1.89 ± 0.23 a	2.65 ± 0.80 a	0.83	0.447
	30-60	1.10 ± 0.32 a	1.54 ± 0.52 a	2.20 ± 0.13 a	3.06	0.063
K (mg/kg)	0-30	50.49 ± 9.18 a	64.58 ± 14.87 a	87.43 ± 21.48 a	2.1	0.142
	30-60	43.99 ± 23.32 a	58.9 ± 11.33 a	80.93 ± 25.53 a	2.46	0.104
CECe (cmol/kg)	0-30	5.56 ± 1.47 b	8.97 ± 2.35 ab	15.37 ± 5.78 a	3.31	0.052
	30-60	4.41 ± 2.14 b	8.65 ± 1.86 ab	15.77 ± 5.48 a	5.21	0.0122*
Cd (mg/kg)	0-30	1.03 ± 0.11 a	0.66 ± 0.35 ab	0.15 ± 0.15 b	5.14	0.0128*
	30-60	1.29 ± 0.19 a	0.91 ± 0.14 b	0.28 ± 0.28 c	46.5	<0.0001***
Sand (%)	0-30	52.27 ± 5.36 a	48.82 ± 6.58 a	47.65 ± 7.58 a	0.5	0.611
	30-60	54.68 ± 9.35 a	48.23 ± 7.59 a	46.60 ± 6.78 a	2.45	0.106
Clay (%)	0-30	20.11 ± 8.25 a	24.35 ± 3.58 a	24.95 ± 4.25 a	2.34	0.116
	30-60	20.53 ± 2.58 a	25.72 ± 4.87 a	26.90 ± 6.87 a	3.42	0.0473*
Acidity	0-30	1.04 ± 0.32 a	1.12 ± 1.87 a	0.10 ± 0.87 a	0.76	0.477
	30-60	1.54 ± 0.47 a	1.34 ± 1.23 a	0.88 ± 0.58 a	0.34	0.714
Al (cmol (+)/Kg)	0-30	0.04 ± 0.04 a	0.38 ± 0.54 a	0.00 ± 0.00 a	2.67	0.088
	30-60	0.09 ± 0.11 a	0.44 ± 0.63 a	0.08 ± 0.32 a	1.24	0.307
Ca (cmol (+)/Kg)	0-30	3.48 ± 1.47 b	6.66 ± 2.58 ab	13.47 ± 7.50 a	2.65	0.09
	30-60	2.22 ± 1.24 b	6.27 ± 2.14 ab	14.14 ± 5.87 a	4.63	0.0187*
Mg (cmol (+)/Kg)	0-30	0.66 ± 0.35 a	0.82 ± 0.53 a	1.10 ± 0.42 a	0.42	0.664
	30-60	0.37 ± 0.42 a	0.79 ± 0.84 a	0.97 ± 0.35 a	3.47	0.0457*

Different letters within each physicochemical parameter indicate statistically significant differences among soil orders at $p < 0.05$, as determined by Tukey's test. ns: not significant; *statistically significant; ***highly statistically significant.

TABLE 3 Cadmium contents in soils, leaves, and cocoa (*Theobroma cacao*) beans from different regions of Peru.

Cd in soils (mg/kg)	Cd in leaves (mg/kg)	Cd in beans (mg/kg)	Cd correlation in soils and leaves	Cd correlation in soils and cocoa beans	Study site	References
0.39	1.12 - 1.28	0.35 - 0.44	Non-significant negative correlation	Non-significant negative correlation	San Martín, Perú	Vallejos-Torres et al. (24)
0.42 - 0.92	0.76 - 1.95	0.48 - 1.15	-----	-----	Piura, Perú	Guarín et al. (23)
0.30 - 0.34	0.36 - 1.63	0.076 - 0.89	-----	-----	San Martín, Perú	Mendoza-López et al. (25)
1.59	2.27	0.86	Non-significant negative correlation	Non-significant negative correlation	Ucayali y Huánuco, Perú	Rosales-Huamani et al. (26)
1.7	2.53	0.99	Non-significant negative correlation	Non-significant negative correlation	Amazonas, Perú	Oliva et al. (21)

and confirms that the multivariate approach appropriately addresses the central hypothesis of the study.

3.3 Spatial variability of total soil cadmium using ordinary kriging

The geostatistical analysis of the spatial distribution of total cadmium (Cd) based on semivariogram modeling in the localities of La Unión and Nuevo San Martín fitted the Linear to Sill model, with a nugget (C_0) of 0.006, a sill ($C_0 + C$) of 0.096 and a range of 1880.12 m. Model performance, assessed through cross-validation, yielded a root mean square error (RMSE) of 0.213 and a coefficient of determination (R^2) of 0.589. Similarly, the spatial distribution of total cadmium in the Perla Mayo locality was also best fitted by the Linear to Sill model, with a nugget of 0, a sill of 0.067, and a range of 825.12 m. Cross-validation reported an RMSE of 0.328 and an R^2 of 0.481. The spatial distribution maps of total Cd obtained by ordinary kriging are shown in Figure 4A for Perla Mayo and in Figure 4B for La Unión and Nuevo San Martín. In Perla Mayo, the interpolated Cd values ranged from ≤ 0.16 mg/kg to > 0.71 mg/kg, with most areas showing concentrations between 0.16 and 0.34 mg/kg. Localized zones with higher values to 0.71 mg/kg in the eastern sector of the study area. In La Unión and Nueva San Martín, interpolated Cd concentrations ranged from ≤ 0.82 mg/kg to > 1.40 mg/kg. The highest values were observed in the northern sector, while the central and southern zones exhibited moderate concentrations 0.82 y 1.01 mg/kg, and the lowest values (≤ 0.82 mg/kg) were located toward the southeastern edge.

4 Discussion

4.1 Physicochemical soil parameters associated with total cadmium across locations and soil profiles

Soils from La Unión at a depth of 0–30 cm exhibited a significantly higher mean Cd concentration (1.35 ± 0.21 mg/kg),

followed by soils from the same location at 30–60 cm depth (1.29 ± 0.19 mg/kg). In contrast, the lowest Cd concentrations were observed in Perla Mayo, with average values of 0.27 ± 0.25 mg/kg and 0.28 ± 0.28 mg/kg at 0–30 cm and 30–60 cm depths, respectively, showing significant differences between the two locations (Table 1). The Cd levels detected in La Unión soils are comparable to those reported by Scaccabarozzi et al. (46), which ranged from 1.1 to 3.2 mg/kg. These findings highlight the need for targeted monitoring in affected areas, as even small portions of cultivated land may exceed the permissible Cd limits for agricultural soils, which range from 1 to 3 mg/kg (47). Although the Cd concentrations observed in this study remain below the maximum permissible limit (MPL) of 1.4 mg/kg established by the Peruvian Ministry of the Environment (24, 48), the highest recorded value (1.35 ± 0.21 mg/kg) approaches this threshold, indicating a potential risk. If exceeded, further chemical speciation would be required to assess Cd bioavailability. It is therefore recommended that new cocoa plantations be established only on agricultural soils with total Cd concentrations below the MPL (23). These findings support the implementation of cadmium management strategies in soils, including restricting new crop establishment in high-risk areas of Cd accumulation (49). Additionally, the studied plots exhibited acidic soil conditions, with pH values ranging from 4.49 ± 0.19 to 5.86 ± 1.12 . According to Arévalo-Gardini et al. (50), the European Union indicates that soil pH values between 5 and 6 correspond to slightly contaminated soils with heavy metals, with contamination risk increasing as pH decreases (51). Cadmium accumulation in soil has been recognized as a serious issue on cocoa farms in Peru (52).

The PCA (Figures 2A, B) reveals that, regardless of soil depth, the same edaphic gradients drive the differences among the three locations. Key soil properties, such as pH, soil organic matter (SOM), and cation exchange capacity (CEC), are the most influential factors affecting cadmium (Cd) accumulation in vegetable crop soils (53). Among these, pH alters the form of cadmium in the soil by affecting its adsorption sites, coordination properties, and surface stability (54). Soil properties and composition, including texture, clay mineral content, and organic matter, also play a crucial role in the presence of cadmium (55, 56).

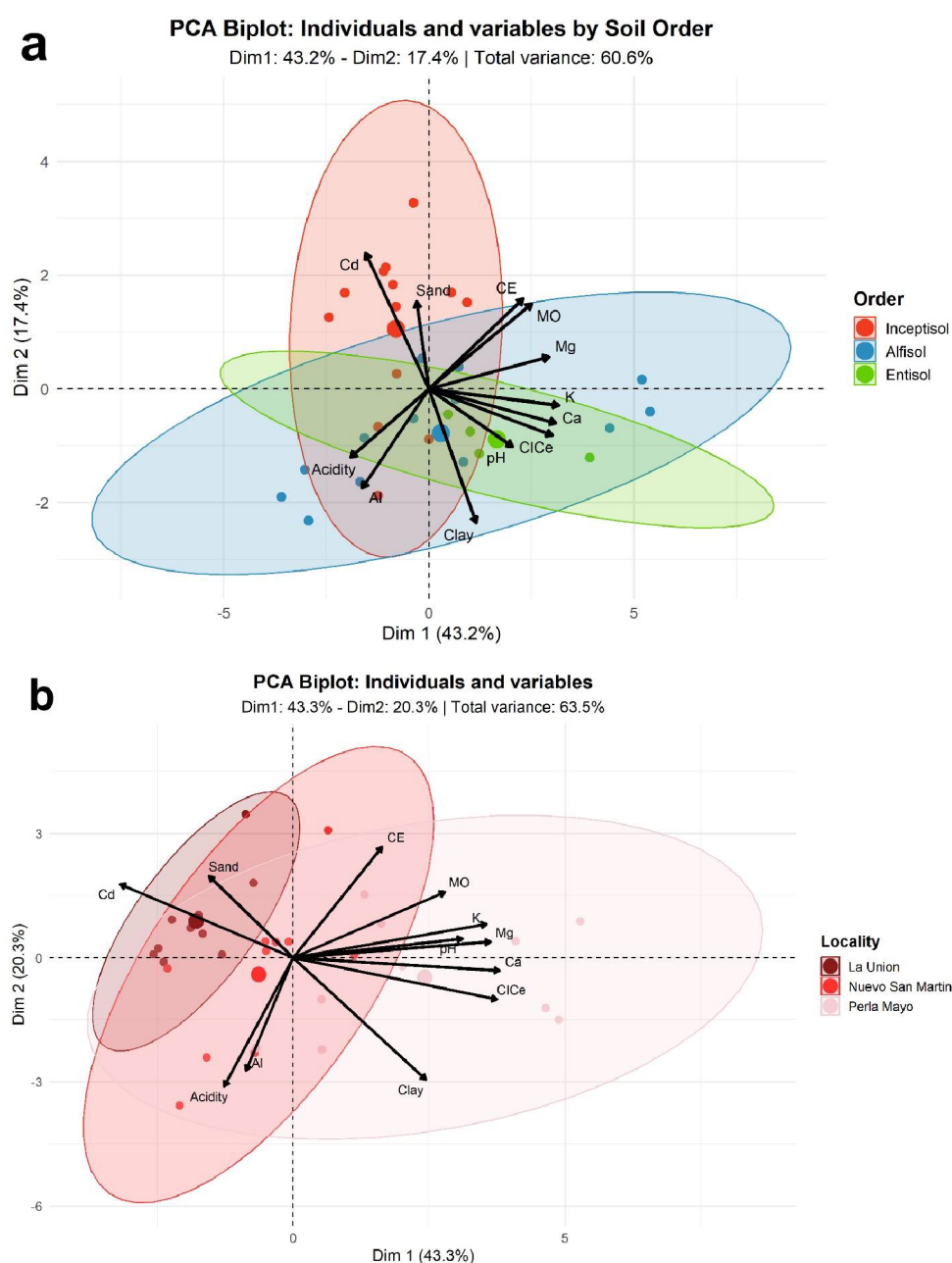


FIGURE 3

PCA at a depth of 0–30 cm (A) and 30–60 cm (B) of soil physicochemical parameters associated with cadmium across soil orders and profiles.

Cd emerges as a secondary yet consistent explanatory variable that distinguishes soil depths within each site and simultaneously covaries with acidity and base saturation. Depth is indeed a key factor influencing Cd content in soils. For instance, Li et al. (29) reported a decline in total Cd concentration from 0.377 to 0.196 mg/kg with increasing depth, and it has been shown that a substantial proportion of Cd may leach from surface layers to deeper soil horizons (57). In the specific case of La Unión, elevated Cd concentrations at the soil surface may also be attributed to the local agricultural practice of incorporating crop

residues (branches, stems, roots, and husks) into the soil as organic fertilizer following decomposition.

4.2 Physicochemical soil parameters associated with total cadmium in soil orders and profiles

Inceptisols at a depth of 30–60 cm exhibited a significantly higher mean Cd concentration (1.29 ± 0.19 mg/kg), followed by

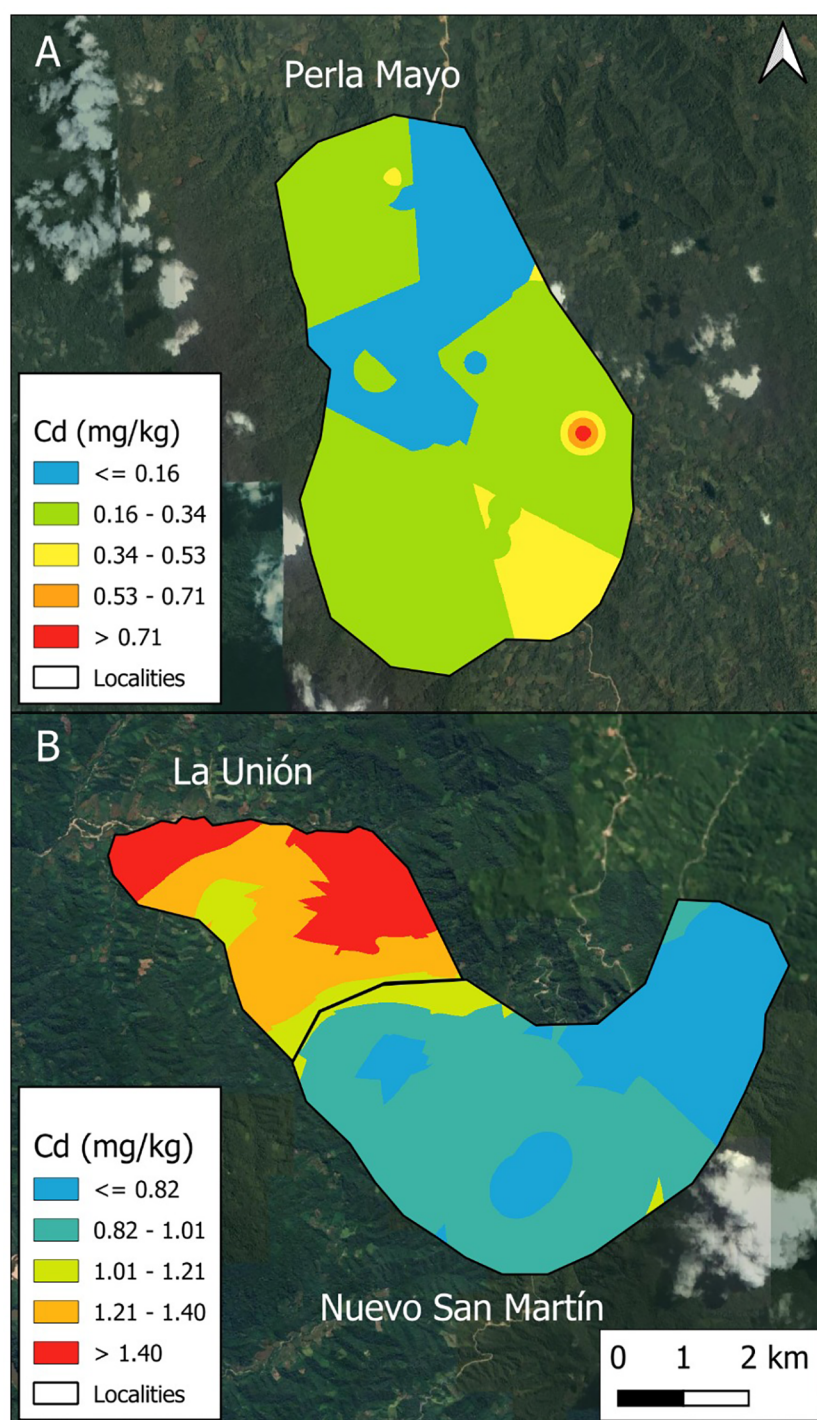


FIGURE 4
Spatial distribution of total cadmium (Cd) in the soil obtained by ordinary kriging. **(A)** Perla Mayo locality. **(B)** Nuevo San Martín and La Unión localities.

Inceptisols at 0–30 cm depth (1.03 ± 0.11 mg/kg). In contrast, the lowest Cd concentrations were observed in Entisols at both 0–30 cm and 30–60 cm depths, with mean values of 0.15 ± 0.15 mg/kg and 0.28 ± 0.28 mg/kg, respectively, revealing statistically significant differences among soil orders (Table 2). The elevated Cd levels in

Inceptisols are consistent with the findings of Sugathas et al. (58), who also reported the highest Cd concentrations in this soil order. In the present study, Cd concentrations followed the trend: Inceptisols > Alfisols > Entisols, indicating that the soil order may have influenced the variation in exchangeable Cd concentrations.

Entisols exhibited the lowest Cd levels, aligning with previous reports indicating that these soils generally contain lower concentrations of metal ions and total Cd (59, 60). Organic matter (OM) content did not differ significantly among soil orders and was generally moderate to high. Nevertheless, the combination of high OM content and low pH, calcium, and magnesium levels observed in this study may have jointly and interactively contributed to the higher Cd concentrations detected in Entisols (58).

The PCA (Figures 3A, B) indicates that Cd responds to both soil acidity and cation exchange capacity. Although its behavior varies slightly with depth or model structure, Cd emerges as a secondary but consistent explanatory variable. Similarly, Elbana et al. (61) and Rechberger et al. (62) reported that soil pH, CEC, and clay content significantly influence Cd retention capacity. In the present study, the main factors influencing Cd content across the different soil orders were CEC and clay content, followed by pH; the latter two variables were corroborated by Zhang et al. (63).

At the surface layer (0–30 cm, Figure 4), Cd shows a negative correlation with pH, indicating that metal availability increases under acidic conditions. This suggests that higher base saturation is associated with lower Cd concentrations. As pH increases, the available Cd content in the 0–30 cm depth soils decreases; conversely, soil acidification enhances Cd availability, consistent with findings from Yi et al. (64), Park et al. (65), Lu et al. (66), and Gu et al. (67). A negative correlation was also observed between Cd and clay content, confirming clay as one of the main factors influencing Cd retention (63). Additionally, a highly significant correlation between Cd and calcium (Ca) was found in soils from Nuevo San Martín.

Soil cadmium values ranged from 0.27 to 1.35 mg/kg; which fall within the ranges reported by Guarín et al. (23) Vallejos-Torres et al. (24), Mendoza-López et al. (25) and are close to the averages found by Rosales-Huamani et al. (26) and Oliva et al. (21) in different regions of Peru. The Cd levels detected in soils from cocoa plantations reflect a similar trend to that observed in cocoa with concentrations ranging from 0.36 y 2.53 mg/kg and cocoa beans, where Cd contents varied between 0.076 and 0.99 mg/kg across various production zones in the Peruvian territory (Table 3).

4.3 Performance of the geostatistical model and spatial structure of total cadmium

The spatial distribution of total cadmium (Cd) showed marked differences among the evaluated localities, with the highest concentrations recorded in La Unión. These variations may be related to differences in soil physicochemical properties such as pH, organic matter, and texture, as well as to local agricultural practices—particularly the use of phosphate fertilizers, which increase Cd

availability (68). The observed downward vertical trend in Cd concentration and its strong dependence on the overlying soil layers could also be associated with the gradual increase in pH from the surface to deeper horizons, suggesting that Cd may also originate from atmospheric deposition or geological transport along the landscape (29). In addition, Cd concentration in the surface layer was correlated with ECEC, K, and Ca at the 0–30 cm depth in the Perla Mayo locality. Cd contamination exhibited significant spatial heterogeneity due to differences in its dynamics between the two depths. Our findings support the design of site-specific control priorities focused on Cd contamination, aiming to implement effective mitigation strategies. The insights gained from this study may contribute to guiding regional efforts to control cadmium pollution, which poses significant risks to cocoa cultivation and food safety (69).

5 Conclusion

The town of La Unión exhibited the highest total Cd concentrations at both 0–30 cm and 30–60 cm soil depths, followed by Nuevo San Martín, while Perla Mayo consistently presented the lowest Cd levels. This suggests that Perla Mayo may be the most suitable location for cocoa cultivation in terms of reduced Cd accumulation. Regarding soil orders, Inceptisols contained the highest Cd concentrations, followed by Alfisols, with Entisols showing the lowest levels, indicating a possible relationship between the degree of soil development and the soil's capacity to retain cadmium. Notably, the conditions in Perla Mayo, located in the province of Tocache in the San Martín region, represent the most favorable scenario due to their low Cd accumulation. This insight is particularly relevant for guiding agricultural management strategies aimed at minimizing Cd uptake in soils under cacao cultivation. Overall, the analyses provide a clear understanding of how cadmium varies with soil depths and edaphic contexts. The medium-to-high uniqueness values (≈ 0.64 – 0.80) confirm that Cd behavior is not entirely explained by the first two components, an expected result for a variable influenced by both the mineral matrix and specific processes, such as anthropogenic inputs. Nonetheless, Cd's consistent contribution to PC2 supports the robustness of the model. Furthermore, the well-defined PCA ellipses and the total explained variance exceeding 60% reinforce the model's reliability. Collectively, the results demonstrate that cadmium is most concentrated in the surface layers of fine-textured, acidic soils across the study sites, thereby fulfilling the objectives of the research.

The spatial distribution of total cadmium (Cd) showed marked differences among the evaluated localities. The highest concentrations were recorded in La Unión, followed by Nuevo San Martín, whereas Perla Mayo exhibited the lowest values—approximately 50% lower than those observed in La Unión.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RS: Conceptualization, Investigation, Writing – review & editing. JC: Funding acquisition, Methodology, Supervision, Writing – original draft. RC-R: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing. NG-J: Writing – review & editing. GV-T: Writing – review & editing.

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