Improving the institutional capacity of Colombia and Ecuador to mitigate trade barriers due the high cadmium levels in cacao

STDF/PG/681

END OF PROJECT REPORT

May 09, 2025

STANDARDS and TRADE DEVELOPMENT FACILITY

KU LEUVEN

PROJECT INFORMATION

STDF/PG/681
Title Improving the institutional capacity of Colombia and Ecuador to mitigate trade barriers due the high cadmium levels in cacao
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Project partners 1. International Center for Tropical Agriculture (CIAT) Recta Cali-Palmira, km 17, Valle del Cauca, Colombia 2. Escuela Politécnica del Litoral (ESPOL), Facultad de Ciencias de la Vida, Vía Perimetral, km 30.5, Campus Gustavo Galindo, Guayaquil, Ecuador 3. Department of Environmental Sciences Wageningen University & Research Droevendaalsesteeg 4, 6708PB, Wageningen 4. Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA) Vía Mosquera, km 14, Bogotá Colombia (originally planned but finally dropped out) 5. Federación Nacional de Cacaoteros (FEDECACAO), Calle 31, No 17-27, Bogota, Colombia
Start date 01/09/2020
End date 31/08/2023, *extended to: 31/12/2024*
Beneficiaries Ecuador and Colombia
Budget Project Total Value: US$ 617,999 STDF contribution: US$ 516,989 Other contribution: total in-kind US$ 101,010

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LIST OF ABBREVIATIONS

Cd	Cadmium
CEC	Cation Exchange Capacity
CRM	Certified Reference Materials
CV	Coefficient of variation
DSM	Digital Soil Mapping
FAAS	Flame Atomic Absorption Spectroscopy
GFAAS	Graphite Furnace Atomic Absorption Spectrometry
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Atomic Emission Spectroscopy
IRM	internal reference materials
MADR	Ministerio de Agricultura y Desarrollo Rural
MAG	Ministerio de Agricultura y Ganadería
MEDXRF	Monochromatic Energy Dispersive X-Ray Fluorescence
QRF	Quantile Random Forest
RF	Random Forest
RMSE	Root Mean Square Error
SOM	Soil Organic Matter
XRF	X-Ray Fluorescence

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1. EXECUTIVE SUMMARY

This STDF project (PG/681) started in September 2020 and, following one extension, was completed in December 2024. It was implemented with an STDF contribution of US$ 516,989 and an in-kind contribution from project partners of US$ 101,010. The requesting organizations were the Ministerio de Agricultura y Desarrollo Rural (MADR) of Colombia and the Ministerio de Agricultura y Ganadería (MAG) of Ecuador. The project was designed to support the cacao sector in the Andean region in complying with new international standards on cadmium (Cd) concentrations in cocoa products.

Limits on Cd in cocoa products were introduced by the European Union on 1 January 2019 and subsequently by the Codex Alimentarius Commission in July 2018, with thresholds depending on cocoa content. In addition, the State of California adopted even stricter Cd limits under Proposition 65, requiring consumer warning labels above specified levels. These regulations disproportionately affect cacao-producing countries in the Andean region because their soils are naturally enriched in Cd compared to other producing regions. Surveys indicated that approximately half of the beans in Ecuador did not meet the often-used cacao bean threshold of 0.6 mg Cd/kg above which beans may not be accepted in the market unless blending of high Cd with low Cd beans is made. At project inception, local institutions were not prepared to cope with the new standards, neither on surveillance nor on implementing good agricultural practices.

The project was set up to improve the institutional capacity of Colombia and Ecuador in managing Cd concentrations in cacao to mitigate the trade barrier imposed by the new standards, using a regional approach. Specifically, the project had three expected outputs:

(1) harmonize methods for cacao sampling and measurement of Cd levels in cocoa and soils according to international standards; thereby preparing the countries for adequate inspection and potential certification/accreditation programs;

(2) improve mapping baselines and mapping capacity for zoning of vulnerable areas in the two countries, based on harmonized methods and data on Cd levels in cacao beans;

(3) develop scientifically sound and context-relevant guidelines on good agricultural practices that lower Cd levels in cacao.

For the first goal, **inter-laboratory proficiency tests** (see section 4.2.1) for Cd concentrations in cacao samples and in soils were organized. For the cacao test, five powdered cacao liquor samples and one commercial cacao powder were used. For the sample with the lowest Cd concentration (median 0.094 mg kg^{-1}), satisfactory results were obtained by only 14 out of 24 laboratories participating. The sample with the highest Cd concentration (median 1.6 mg kg^{-1}) was adequately measured by 21 out of 24 laboratories. Regarding the soils test, four samples were used. Only 11 out of 24 participants reported satisfactory results for the sample with the lowest Cd concentration (median 0.060 mg/kg). The sample with the highest satisfactory results (median 1.5 mg/kg) was adequately measured by 21 out of 24 laboratories. More unreliable data were obtained when Atomic Absorption Spectroscopy (AAS)[1] rather than Inductively Coupled Plasma (ICP)[2] instruments were used, or where concentrations were outside the calibration range. The partners of this project set up additional work to **identify the variability due to sampling**. Hierarchical sampling of four commercial lots in Ecuadorian warehouses was made to identify the variation among beans, bags, and replicate chemical analyses of ground samples. This showed that a composite sample should be made from at least 10 bags on a pallet, and at least 60 beans should be ground before analysis to obtain an acceptable coefficient of variation below 15%. **This work shows that current Cd**

[1] Atomic Absorption Spectroscopy refers to the measurement method of *atomic spectroscopy* for measuring the amount of a chemical element based on the measurement of the absorption of characteristic *electromagnetic radiation* by atoms in the vapour phase (source: International Union of Pure and Applied Chemistry. 'atomic absorption spectroscopy' in *IUPAC Compendium of Chemical Terminology*, 5th ed., Online version 5.0.0, (2025). https://doi.org/10.1351/goldbook.08451)

[2] Inductively Coupled Plasma refers to plasma produced by induction by means of a high-frequency (about 2500 Hz) electromagnetic field. The region of gas at high temperature and free from the field is taken as the region of observation (source: International Union of Pure and Applied Chemistry. 'inductively-coupled plasma' in *IUPAC Compendium of Chemical Terminology*, 5th ed., Online version 5.0.0, (2025). https://doi.org/10.1351/goldbook.08488).

analyses in cacao on the market are neither sufficiently accurate nor precise; more control on laboratory certifications is needed for reliable screening of Cd in cacao. All participating laboratories received their scores and personal (written) feedback on their procedure. Some of them received additional live training for sample preparation, analysis, and quality control.

The second goal was to construct predictive **maps of Cd concentrations in beans** of Ecuador and Colombia. For this, we joined forces with the DeSIRA project "Clima-LoCa"[3], through which additional high-quality data on bean and soil composition of Ecuador and Colombia were collected and collated. Maps were calibrated to 70% of the data (n=2146) and were then tested on the remaining 30% of data to identify the precision of the prediction. The results show that the Cd concentrations in beans of an individual tree are, on average, well predicted, but that the uncertainty around the prediction, expressed as the width of the 95% confidence interval, was > 4 of the mean, clearly an unacceptably large uncertainty. Additional work showed that mean Cd concentrations for a larger number of trees (e.g. mean of field) are well predicted (see output 5 below).

The third goal was to develop scientifically sound and context-relevant **guidelines on good agricultural practices** that lower Cd levels in cacao. A meta-analysis was made of the 10 field trials in Ecuador, where soil amendments had been tested to lower Cd in cacao beans, these field trials had started before this project started. Data was collected up to five years after the first soil amendment. The results are expressed in the factor that reduces bean Cd concentrations due to the intervention compared to the corresponding non-amended control treatment. These "reduction factors" are low; only the amendment of compost, lime, gypsum, and fertilizers yielded an average Reduction Factor (RF) above 1, e.g., maximally 1.3 for fertilizers. To put this in perspective, the Ecuadorian national average bean Cd is about 0.9 mg Cd/kg, and applying this RF to that value (i.e., assuming *all* fields are treated with fertilizers) would yield 0.9/1.3= 0.7 mg Cd/kg, still above the threshold of 0.6 mg Cd/kg, showing the limitation of (costly) soil amendments.

For pragmatic reasons, **two additional and new project outputs** (outputs 4 & 5) were defined during implementation. Output 4 "Test a new benchtop XRF based equipment for fast screening of Cd concentrations in nibs, soil and leaves" was defined because a relatively cheap and brand-new equipment came on the market for screening Cd in beans in 2022. It became much faster and easier to work with this new machine than with the conventional ICP-MS method. The STDF agreed that the implementation group would spend efforts on identifying the power of this equipment; this also explains the 1-year extension of the project. This new equipment is a robust portable Monochromatic Energy Dispersive X-ray Fluorescence (MEDXRF, here sometimes referred to as simply XRF), an alternative to ICP-MS, requiring no laboratory (can be used on site) and very little training. In total, 112 bean, 19 cacao liquor, 75 leaf, and 108 soil samples were analyzed by the new and by the established ICP-MS technique, which resulted in a high accuracy and precision relationship between ICP-MS data (x) and MEDXRF (y): $y = 1.013\,x + 0.004$, $R^2 = 0.984$ (both in mg Cd kg^{-1}). For a measurement time of 200 s, the coefficient of variation (CV) among three replicates increased above 15 % around a Cd concentration of 0.1 mg kg^{-1}, indicating that care should be taken below this concentration. Based on this data, the proposed protocol is to analyze three replicates for 200 s with a sample size sieved below 500 µm. **The optimized MEDXRF technique offers advantages in terms of cost-effectiveness and efficiency for routine monitoring in the cacao supply chain**, large-scale screening, and scientific research. It allows blending high with low Cd beans and allows exporting lots that meet the thresholds set by commercial buyers. The implementing partners have published that method and disseminated the information. This equipment has now been bought in Ecuador and Colombia by research and commercial partners.

Output 5 "Explore the potential of mechanistic geochemical models to predict Cd availability in soils and Cd accumulation in beans and evaluate the best method for predicting bean Cd concentrations in areas where cacao is not yet planted based on soil map data or on soil analyses", is related to predicting bean Cd concentrations in areas without cacao (**expansion areas**). Given the considerable rise in cacao prices in 2024-2025, there was a sudden need to estimate bean Cd based on either soil analyses (pre-planting) or the digital soil map. For 691 validation data in Ecuador and Colombia, we compared either (1) conventional soil analysis and predictions with a statistical model; (2) soil extractions for "bioavailable Cd"; and (3) the digital soil map (made as part of Output 3). It was shown that the precision for individual trees ranked (1)>(3)>(2), but that for regional means, the digital soil map (3) is the best and the cheapest option (no soil analysis necessary). The regional

[3] https://climaloca.org/

means are markedly well predicted within a concentration class. For example, in the critical zone of bean Cd concentrations between 0.3-1.2 mg Cd/kg, the **mean observed Cd concentrations are within a factor of 1.2 of predictions** in concentration classes of 0.1 mg Cd/kg (e.g., between 0.4-0.5, 0.5-0.6, 0.6-0.7, etc.). **This result is promising**: this new map can identify regions where production is not affected by the limits, regions where remediation is possible, and limits where export to the EU is not possible unless with strong interventions.

The project also supported and complemented the regional project STDF/PG/577 "Coordinating management of cadmium levels in cocoa in Latin America and the Caribbean" led by IICA. This project has shared the reference samples of cocoa liquor with the consensus values of Cd concentration. We also processed the data of the laboratories involved in project STDF/PG/577 and provided the implementing agencies with a training that was comparable to the laboratory training given to the laboratories. All participants of the proficiency tests of both projects also have additional samples to use as reference materials; we know this is a method to ensure quality control in their analyses. Most importantly, the very recent demonstration of the value of the digital soil map and the value of the portable MEDXRD equipment, both of which can be used to identify the regions of concern and methods to make blends below the expected thresholds.

Main achievements (non-technical summary)

Overall, the project helped Colombia and Ecuador respond more effectively to the challenge of Cd in cacao by strengthening practical tools, skills, and coordination across the value chain. Laboratories improved their ability to measure Cd accurately and consistently, reducing uncertainty in test results that affect market access. Producers, processors, and technical staff gained clearer guidance on realistic options to manage Cd-related risks. A major achievement was the successful introduction of a fast, low-cost portable testing technology (MEDXRF), which allows Cd levels to be checked quickly on-site without the need for complex laboratories. In addition, the project produced detailed risk maps showing where Cd levels are likely to be high or low, supporting better decisions on sourcing, blending, and future cacao expansion. Close collaboration between public institutions, research organizations, and private-sector actors in Ecuador and Colombia strengthened regional coordination and laid the groundwork for more reliable, sustainable, and trade-compliant cacao production.

Key lessons learned and sustainability considerations

The project demonstrated that addressing Cd as a trade barrier requires a combination of robust analytical capacity, harmonized sampling protocols, and spatially explicit risk management tools. A key lesson learned is that laboratory variability and inadequate sampling procedures can undermine regulatory compliance as much as high Cd concentrations themselves, underscoring the importance of continued investment in quality control, training, and accreditation.

From a sustainability perspective, the project strengthened long-term institutional capacity by embedding harmonized methods, reference materials, and low-cost screening technologies within national and private-sector monitoring systems. The digital Cd risk maps and predictive tools support environmentally sustainable cacao production by helping avoid unsuitable expansion areas and reducing the need for costly remediation. Together, these outcomes contribute to more resilient cacao value chains, safeguard smallholder livelihoods, and support continued access to international markets under evolving SPS requirements.

2. OVERVIEW

2.1 Background and context

This project was written by the requesting organizations of Colombia and Ecuador to support the cacao sector of the Andean region comply with new international standards on the concentration of Cd (further abbreviated as Cd) in cocoa products; these regulations were very recent and could considerably affect the sector. It was felt that the local **institutions were not prepared to cope with the new standards, neither on surveillance nor on implementing good agricultural practices**. This proposal addressed the issue, through a coordinated regional approach with participation of Colombia and Ecuador, and has relevance and potential implication in Peru.

The European Union (EU) established limits on Cd in cacao-derived products.[4] The limits entered into force on January 1, 2019. The limits refer to Cd concentrations in the final product, not in the bean and the limits depend on the cocoa content of the product. On July 2, 2018, the Codex Alimentarius Commission has also defined, for the first time, limits for contamination of naturally occurring contaminants found in chocolate, the limits for Cd are 0.8 or 0.9 mg Cd/kg of chocolate, depending on the cocoa content. These Codex limits are very close to the EU (EU: 0.8 mg Cd/kg for chocolate >50% cocoa; Codex: 0.8 mg Cd/kg for chocolate with cocoa between ≥50-<70% and 0.9 mg Cd/kg for those with cocoa ≥70%.). The state of California has agreed in February 2018 on even stricter Cd limits for chocolate products under Proposition 65, above which consumers will be warned through product labelling. With the Codex adoption, it is foreseeable that several other countries will follow soon.

The **limits mainly affect the cacao sector in the Andean Region**, the reason being that the soils are naturally more enriched in Cd compared to that in other cacao producing regions, an aspect also acknowledged in the new Codex Alimentarius by referring to the Cd issue in cacao as **a naturally occurring contaminant**. Multi-elemental fingerprinting analysis of a global collection of cacao beans of different origin showed that the concentration of Cd in beans from South America were nearly three times higher than those from Central America and East Africa and ten-fold above those of West Africa.

The socio-economic impact of these new and upcoming regulations in Colombia and Ecuador couldn't yet be calculated precisely. Surveys of the extent of Cd concentrations in the beans were indicative that 30-50% of the beans may not be accepted unless blending of high Cd with low Cd bean is made.[5] The EU regulation and the Codex limits the concentration of Cd in the final product, not in the beans. There is no unique conversion from a chocolate limit to a bean limit but **a maximum concentration of 0.6 mg Cd/kg bean**, with or without peeling, **is often informally** used among buyers. Indeed, assuming that beans contain about 50% butter (an average value), then the concentration of Cd in the cocoa powder would be 1.2 mg Cd/kg for peeled beans (nibs) with 0.6 mg Cd/kg. Thus, if chocolate with 70% cocoa solid is produced from this cocoa mass the final concentration of Cd will be 0.8 mg Cd/kg, which is within the allowable limits. National surveys show that the average concentration in peeled beans of Ecuador is 0.90 mg Cd/kg (n=560; data of 2017 by KU Leuven group)[6]. In other national surveys of Honduras, Trinidad and Peru, averages are of the same order of magnitude as reviewed in 2021.[7] No nationwide surveys are publicly available for Colombia but information from two informal sampling campaigns (n=638) indicate that about 80% of the collected beans contain Cd concentrations above 0.5 mg Cd/kg with 52% surpassing the 1

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[4] European Commission, "Commission Regulation (EU) No. 488/2014 of 12 May 2014 Amending Regulation (EC) No. 1881/2006 as Regards Maximum Levels of Cadmium in Foodstuffs," *Official Journal of the European Union* L 138 (May 13, 2014): 75–79, https://eur-lex.europa.eu/eli/reg/2014/488/oj/eng
[5] Ruth Vanderschueren, et al., "Cadmium Migration from Nib to Testa during Cacao Fermentation Is Driven by Nib Acidification," *LWT* 157 (2022): 113077, https://doi.org/10.1016/j.lwt.2022.113077
[6] David Argüello et al., "Soil properties and agronomic factors affecting cadmium concentrations in cacao beans: A nationwide survey in Ecuador," *Science of The Total Environment* 649 (2019): 120-127, https://doi.org/10.1016/j.scitotenv.2018.08.292
[7] Ruth Vanderschueren, et al., "Mitigating the level of cadmium in cacao products: Reviewing the transfer of cadmium from soil to chocolate bar". *Science of The Total Environment*,781,2021,146779, https://doi.org/10.1016/j.scitotenv.2021.146779.

mg Cd/kg bean. Without doubt, **the average bean Cd concentrations exceed the limit and illustrate the extent of the issue, a significant trade barrier that was already felt by the countries and expected to impact even more strongly after January 1st, 2019**.

The objective of this project was to improve the institutional capacity of Colombia and Ecuador in managing Cd concentrations in cacao **to mitigate the negative impacts of the trade barrier imposed by the new Cd standards.** The implementing partners of this project had been working on this topic and have experienced several technical and organizational issues, including: (1) lack of harmonization and quality control in the surveillance programs and laboratory procedures; (2) incomplete zoning of the vulnerable areas and recommendation domains, either because of lack of data or because of concerns about sharing data; (3) lack of knowledge on Cd risks for identification of suitable land for cacao expansions; and (4) lack of coherent scientifically demonstrated and context-relevant agricultural practices to lower Cd in cacao. These priorities were confirmed during the International Workshop on Cadmium Reduction in the Andean Zone "CacaoCdFREE" (12-14 March 2018) organized by CIAT and CIRAD in Colombia, and at meetings discussing national actions, e.g. as organized in Bogota (29 June 2018 by the Swiss cooperation and in Lima 18 July 2018 by the Ministry of Agriculture of Peru) with the participation of multiple stakeholders from Colombia, Ecuador and Peru, including research, government institutions and private sector.

One of the main gaps encountered in the mentioned countries to address the Cd issue was the **lack of quality control** on the data of Cd concentrations in beans and associated soils. From the published scientific literature of Cd in cacao conducted in the region (i.e. Ecuador, Peru and Colombia), the **majority of the studies did not include quality control programs** with certified reference materials that are indispensable to assure the quality of the measurements of Cd. Many of the studies have not used the modern, but more expensive ICP-MS instrument, for Cd measurement which is preferable for the detection of low concentrations. Reliable soil and bean Cd data is needed not only for research purposes but also for government planning and commercialization. For that reason, a harmonization program on sampling, sample treatment and sample analysis should be set up that meets international standards, including informing the government institutions and training of the inspectors.

The EU regulation on Cd in cacao was announced in 2014, and since then efforts had intensified in Colombia, Ecuador and Peru to map the areas (zoning) where Cd concentrations are high. It had been confirmed that the contamination is not random but that there is significant spatial association, i.e. hot spot regions stretching >100 km^2. However, this **zoning was incomplete**, as most of the data collection conducted had been scattered across several private and public sector entities which had restricted the sharing of information within and between the affected countries. Therefore, this project wanted to harmonize data collection with gap filling surveillance of some regions and the maps would be made with a scientifically validated state-of-the art approach through involvement of GIS experts in each country.

Finally, it was proposed to coordinate and facilitate the collating of information from field trials on the potential of agronomic countermeasures, followed by a synthesis of trends and lessons, and dissemination of recommended practices to extension workers. This data gathering and training, combined with the translation of the information into context-relevant recommendations for Cd mitigation practices, **illustrated collaborative and inter-disciplinary approaches focused on the research/technologies for mitigation and remediation.**

2.2 SPS context and specific issue/problem to be addressed

2.2.1 Sustainability and future trends of cacao production in Colombia and Ecuador due to Cd constrains.

Latin America currently produces about 17% of the world cacao, a share that is expected to continue growing. The major producers of cacao in the region are Ecuador (375,000 MT), Brazil (296,000 MT), Peru (167,000 MT) and Colombia (60,000 MT). Latin America is currently responsible for about 80% of all fine flavour cacao production in the world. Ecuador is the main producer, but other Latin American countries, such as Peru, also play an important role. For Ecuador, cacao is an important agricultural product for its economy representing about 4% of the total export (excluding oil). The EU and the USA are the main export markets. About 560,000 ha are planted with cacao in nearly all provinces of the country. It is estimated that the cacao sector **generates 600,000 jobs**; its market chain represents 4% of the economically active population and 12.5% of the agriculture economically active population of the country.

In Colombia, it is estimated that more than 54,000 families are involved in cacao cultivation, with plots dispersed across the country in the Caribbean region, passing through the Andean mountain ranges to the northern Amazon and the south-western Pacific coast. Cacao exports currently play a small role in the national economy and cacao production is mostly targeting the national market, with relatively low production levels of about 400 kg/ha on average. This scenario is expected to change in the coming years. Since the initiation of the peace agreement between the Colombian government and the FARC there is increased **support, both from the national government and through international cooperation, to expand cacao cultivation** and replace illicit crops in post-conflict areas. Moreover, in some regions in Colombia cacao is partly replacing coffee as a commodity due to the negative impacts of climate change on coffee production. Many traders, sector representatives and producer organizations are considering the international market as the target outlet for the future production of recently planted and projected new areas across Colombia, with a focus on value addition, targeting the growing international market for fine and flavour and **deforestation-free cacao.**

2.2.2 Institution framework for SPS management in Colombia and Ecuador

Ecuador

The Agency for Regulatory and Control of Plant and Animal Health (AGROCALIDAD) is a governmental institution adjoined to the Ministry of Agriculture (MAG) that controls, promotes and regulates agricultural health and food safety by following national and international standards. The Agency is responsible for the development and implementation of food safety and environmental sound agricultural practices and works together with the private sector for the execution of plans, programs and projects. AGROCALIDAD is the agency that has represented the country in the various meetings held by the Codex Committee on Contaminants in Foods (CCCF, Joint FAO/WHO Food Standards Program) taking an opinion on the proposed draft for maximum levels for Cd in chocolate and cocoa products in order to protect the health of consumers and ensure fair practices in food trade.

For SPS management in the cacao chain in Ecuador private organizations play an important role. For example, the National Association of Cacao Exporters (ANECACAO) supports and campaigns through their associates on the implementation of good agricultural practices for cacao production. The association also works together with local authorities, universities and other private institutions to carry out training programs for cacao producers on SPS measures. This includes providing technical assistance on pest and disease management, and the implementation of mitigation strategies.

Colombia

The Colombian cacao chain differs from the Ecuadorian in that global multi-nationals play a limited role. Two Colombia-based companies, Nutresa and Casa Luker, purchase nearly 80% of Colombian cacao bean production, with the remaining volumes flowing to small chocolate manufacturers and international markets. These firms play an active role in increasing cacao production through commercial alliances with farmers, research, technical and social support. The national federation of cacao producers (FEDECACAO) represents 38,000 smallholder farmers in 22 departments of Colombia, and is focused on research, technology transfer and commercialization. They are the primary provider of technical assistance, mainly present in the high production areas of the country.

So far, a strong national institutional leadership on the Cd problem is still lacking in Colombia, despite widespread concerns throughout the sector, as informal data gathering suggests that they might be the most affected country by the regulation. There is also great concern among the international community due to potential implications for the post-conflict strategy. Various actors have emphasized the need for national and regional coordination and international donors have supported a number of meetings, that have helped to set priorities including the need for knowledge sharing, mapping, technical support and field-based research to mitigate high Cd levels in cacao beans.

In summary, the capacity for SPS management on the issue of Cd in cacao seems to be more developed and with a clear institutional leadership in Ecuador than in Colombia.

3. PROJECT IMPLEMENTATION

Date	***Activities***	***Notes***
01/09/2020	*Signature of grant agreement and formal project start with steering committee*	
28/02/2021	*First progress report:* • *Consortium agreements signed by all partners* • *Cacao samples for proficiency test collected and distributed* • The Federación Nacional de Cacaoteros (Fedecacao), previously an Associate Partner, was included as a Project Partner. The Instituto Nacional de Metrología de Colombia (INM) also joined the Project as an Associate Partner	*Agrosavia finally did not sign the agreement because they were not allowed to sample soils and disseminate the sampling*
31/08/2021	*Second progress report* • *First proficiency test (cacao) completed (output 1)* • *Soil samples for second proficiency test collected (output 1)*	
28/02/2022	*Third progress report* • *Second proficiency test (soils) completed (output 1)* • *Bean sampling strategy in warehouse completed (output 1)*	
31/08/2022	*Fourth progress report* • *All proficiency test reports and individual reports for participants written and distributed (output 1)* • *Output 3 was reduced because not a lot of new information on agricultural practices was available* • *Instead, output 4 (new XRF equipment for fast, cheap and easy Cd measurements) and output 5 (best predictive method for bean Cd concentrations) were added* • *XRF equipment successfully tested (output 4)* • *Sampling for mapping ongoing (output 2)*	
20/12/2022	*Formal approval for a requested no-cost extension of the project until 31/12/2024 because of pandemic and because of the collaboration with Clima-Loca which also ran until 12/2024.*	
30/06/2023	*Fifth progress report* • *Internship of Ecuadorian technician Elias Garcia at KU Leuven (analytical techniques for Cd analysis and quality control) (output 1)* • *Preparation of presentation for lab trainings and written guidelines (output 1)* • *Scientific paper on Cd variability in warehouses and laboratory analyses (output 1)* • *Additional sampling done (output 2)*	*Due to internal restructuring, INM withdrew from the project, as the timing no longer aligned well with their planning.*
31/12/2023	*Sixth progress report* • *Five laboratory training sessions were organized (output 1)* • *Written guidelines on lab practices (output 1) and scientific publication on the XRF equipment (output 3) prepared.* • *Mapping sampling finished and statistical analysis started (output 2).*	
30/06/2024	*Seventh progress report* • *Lab guidelines finished (output 1)* • *Data gathered to compare peeled versus unpeeled beans (output 1)* • *A digital soil mapping training was organized (output 2)* • *XRF paper was finished an submitted (output 3)* • *150 soils collected and extractions done (output 3)*	
31/12/2024	*End of project*	
09/05/2025	*Final project report and end-of project assessment*	

STANDARDS and TRADE DEVELOPMENT FACILITY

KU LEUVEN

Implementing agency
KU Leuven - Belgium
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Start Date
01/09/2020
End Date
31/08/2023, *extended to: 31/12/2024 (at the end of 2022). Formal approval for a requested no-cost extension of the project until 31/12/2024 granted by the STDF Secretariat, due to the COVID-19 pandemic and to ensure alignment and collaboration with Clima-LoCa which also ran until 12/2024.*
Adjustments
In 2023, Output 4 "Test a new benchtop XRF based equipment for fast screening of Cd concentrations in nibs, soil and leaves" and Output 5 "Explore the potential of mechanistic geochemical models to predict Cd availability in soils and Cd accumulation in beans and evaluate the best method for predicting bean Cd concentrations in areas where cacao is not yet planted based on soil map data or on soil analyses" were added in the project activity. The rationale lies in the fact that Output 3 "Develop scientifically sound and context-relevant guidelines on good agricultural practices that lower Cd levels in cacao" did not present sufficient new data on agricultural practices to develop new guidelines. The output was changed, with STDF approval, to (3a) evaluating Monochromatic Energy Dispersive X-Ray Fluorescence (MEDXRF) as a cheaper, faster and easier alternative to the conventional method (i.e. ICP-MS) for quantifying Cd concentrations in soil and cacao samples and (3b) expanding the study of Wietse Wiersma from Wageningen to better predict Cd availability and uptake through multiple soil extraction methods and mechanistic modelling.
Steering Committee
The Project Steering Committee brought together key stakeholders, specifically representatives from the requesting organizations - the Ministerio de Agricultura y Desarrollo Rural (MADR) of Colombia and the Ministerio de Agricultura y Ganadería (MAG) of Ecuador - as well as representatives of the implementing agencies (KU Leuven, CIAT, ESPOL, Wageningen University & Research). The Steering Committee convened regularly, virtually and in person, alongside project meetings and technical workshops. Additional stakeholders were associated at different points of the project. The Federación Nacional de Cacaoteros (FEDECACAO) joined as a project partner after initially being listed as an associate partner. The Instituto Nacional de Metrología (INM) of Colombia also joined as an associate partner, though later withdrew due to internal restructuring and timing constraints. AGROSAVIA, initially included as a partner, did not sign the consortium agreement and withdrew early in the project given sensitivities around sharing sampling data.

4. ACHIEVEMENT OF RESULTS

4.1 Project goal and outcome level results

Project Goal: *The cacao sector in Ecuador and Colombia remains competitive*.

Indicator: *Increase in employment rates in the cacao sector*.

Project Outcome: *To improve the institutional capacity of Colombia and Ecuador in managing Cd concentrations in cacao to mitigate the trade barrier imposed by the new Cd standards, using a regional approach*.

Indicators: *1) Sustain or increase of the export volume of cacao beans in Ecuador and Colombia, 2) Cacao beans or derived products originating from Ecuador and Colombia are not rejected or received an alert notification at the European border due to high levels of Cd.*

At the start, the project had three outputs and during implementation, *two outputs, i.e. (4) and (5) were added in consultation with the STDF Secretariat.*

(1) harmonize methods for cacao sampling and measurement of Cd levels in cocoa and soils according to international standards; thereby preparing the countries for adequate inspection and potential certification/accreditation programmes;

(2) improve mapping baselines and mapping capacity for zoning of vulnerable areas in the two countries, based on harmonized methods and data on Cd levels in cacao beans;

(3) develop scientifically sound and context-relevant guidelines on good agricultural practices that lower Cd levels in cacao.

(4) test the new benchtop XRF based equipment for fast screening of Cd concentrations in nibs, soil and leaves (added in 2023).

(5) evaluate the best method for predicting bean Cd concentrations in areas where cacao is not yet planted based on soil map data or on soil analyses (added in 2023).

4.2 Output 1: Harmonize methods for cacao sampling and measurement of Cd levels in cocoa and soils according to international standards; thereby preparing the countries for adequate inspection and potential certification/accreditation programs.

One of the main gaps encountered in the mentioned countries to address the Cd issue is the **lack of standardized protocols and quality control** on the data of Cd concentrations in beans and associated soils.

The first problem is the analytical one, i.e. the analytical detection and the lack of sound reference materials. The second problem is the yet unknown sample heterogeneity in bean Cd concentrations.

4.2.1 Inter-laboratory proficiency test of cacao and soils

Proficiency tests are inter-laboratory comparison exercises designed to evaluate the analytical performance of participating laboratories by comparing their results against assigned or consensus values. They aim to assess data quality, identify methodological inconsistencies, and support harmonization of analytical procedures across laboratories.

Five cacao liquor (pure solid cacao mass) samples were collected from local cacao producers in Ecuador and Colombia. The samples were pulverized in a Grindomix®200 mixer with liquid nitrogen. **One commercial cacao powder** was included in the proficiency test **as a sixth sample**. Polypropylene pots were filled (approximately 40 g of sample per pot) and sealed with parafilm to distribute to the participating laboratories. Homogeneity was tested by analysing the Cd

concentration of eight replicates of 100 mg each for two random samples (KUL 3 and 4) at the laboratory of the implementing Partner (KU Leuven).
The proficiency test was organized according to a simultaneous participation scheme. Twenty-one laboratories in Latin America (nine in Ecuador, twelve in Colombia, and two in Peru) and two European laboratories, used for benchmarking purposes, participated between May and July of 2021. The results of the laboratories were compared to the consensus values (see below) to show the performance of the individual participants and of the group. Each round, a questionnaire was distributed to the participants to gather information on lab protocols, equipment, materials, and quality control. More details can be found in the report of 2021, **Annex 1** of this report.

The data of the proficiency test was analysed with ISO guidelines.[8] The performance of each participant was quantified by calculating a **z'-score** for each sample described in detail in the paper written on this test[9] (, see **Annex 5**). **A score of |z'| ≤ 2 was considered acceptable.**

The homogeneity checks on 8 subsamples of 100 mg each of sample KUL 3 and KUL 4 yielded a coefficient of variation (standard deviation/mean*100, in %, CV) of 6.4 % and 3.1 %, respectively. The consensus values ranged between 0.094 and 1.6 mg Cd kg^{-1} (Table 1), i.e., below and above the Cd limits commonly used and described in the introduction. For samples KUL 1 and 6, $u(x_{pt}) < 0.3\ \sigma_{pt}$ so the standard uncertainty was negligible. The allowed deviation from the consensus values ranged from 31 to 47 % depending on the sample.

Table 1. The Cd concentrations in six reference cacao samples: the consensus value (x_{pt}), the standard uncertainty of the consensus value ($u(x_{pt})$), the standard deviation for proficiency assessment (σ_{pt}) and the corresponding acceptable range of each sample in the proficiency test by equating z_i' to -2 and 2 (in mg Cd kg^{-1}).

Sample	x_{pt} (mg Cd kg^{-1})	Acceptable range (mg Cd kg^{-1})
KUL 1	0.81	0.54 - 1.1
KUL 2	0.095	0.051 - 0.14
KUL 3	1.6	1.1 - 2.1
KUL 4	1.2	0.79 - 1.6
KUL 5	0.45	0.27 - 0.62
KUL 6	0.30	0.19 - 0.42

[8] International Organization for Standardization, "Statistical methods for use in proficiency testing by interlaboratory comparison", 13528:2015, ISO 13528:2015 - Statistical methods for use in proficiency testing by interlaboratory comparison
[9] Jesse Dekeyrel et al., " Using optimized monochromatic energy dispersive X-ray fluorescence to determine the cadmium concentration in cacao and soil samples", *Helyion* 10, n. 20 (2024), e39034, https://doi.org/10.1016/j.heliyon.2024.e39034

Figure 1 illustrates the reported Cd concentrations of each laboratory for sample KUL 1. This graph shows that the acceptable range according to the ISO guidelines is equivalent to 34 % of the consensus value whereas z' = 1 is equivalent to 17 %.

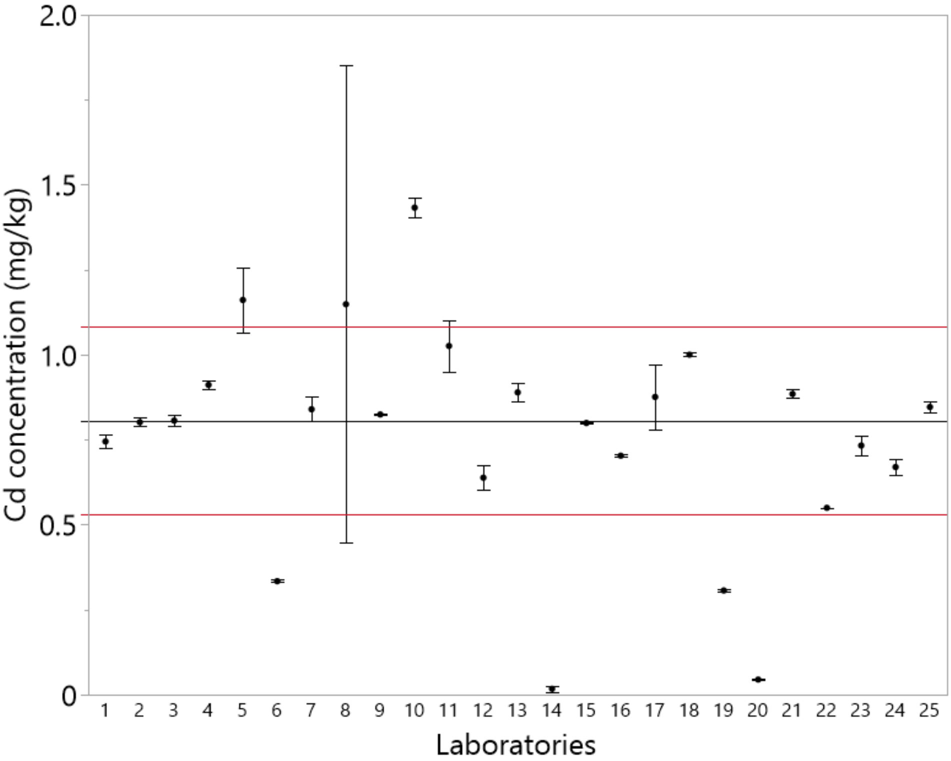


Figure 1. Reported Cd concentrations (mg kg^{-1}) of each laboratory for cacao liquor sample KUL 1. The middle black line represents the consensus (median) value for the sample (0.81 mg kg^{-1}) and the outer red lines represent the acceptable range (0.54 – 1.1 mg kg^{-1}) calculated from z'-scores -2 and 2.

Out of the 25 laboratories that participated, thirteen (52 %) reported acceptable results for all six samples. From these thirteen laboratories, four had a systematic deviation from the consensus values (all z'-scores higher or lower than zero). Seven laboratories (28 %) reported an unacceptable result for one of the test samples. Five laboratories (20 %) reported unacceptable results for at least two samples.

On average, 76 % of the laboratories reported acceptable results per sample. The robust coefficients of variation (rCV) among the 23 Latin American laboratories ranged from 19 to 26 % depending on the sample with an average of 23 %. In the proficiency test with Cd in dried fish food organized by the JRC, the rCV among 41 (mostly European) laboratories was 9.5 % and 39 laboratories (95%) reported acceptable results. Pereboom et al. (2016) found rCVs for total Cd concentration in two feed samples of 5.9 and 6.0 % among 21 European laboratories. For one sample 20 laboratories (95%) had acceptable results (consensus value 0.37 mg/kg). For a second sample with a consensus value of 0.62 mg/kg, all laboratories (100%) reported satisfactory results.

The substantially higher inter-laboratory variability and lower proportion of acceptable results observed in the present proficiency test indicate a clear need for further capacity building and harmonization of analytical procedures among participating laboratories. These findings directly motivated the implementation of targeted laboratory training and methodological support under Activity 1.4 of this project.

The data from the questionnaire indicated that, from the 23 participating laboratories in Latin America, six used Flame Atomic Absorption Spectroscopy (FAAS), eight used Graphite Furnace Atomic Absorption Spectrometry (GFAAS), five used Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-OES) and three used Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to analyse the Cd concentration in cacao samples. Figure shows that, overall, absolute z'-scores varied ICP-MS < ICP-OES < AAS especially at low Cd concentrations (sample KUL 2). It is somewhat surprising that GFAAS did not perform better as the detection limits of GFAAS are generally better than that of ICP-OES, suggesting that the operators are not sufficiently trained in GFAAS. Only five laboratories reported the use of certified reference materials (CRMs) for the quality control of their analyses. Nine laboratories used internal reference materials (IRM) and eight laboratories did not use any type of reference sample for quality control. Additionally, seven labs reported using no method blanks as an additional step of quality control.

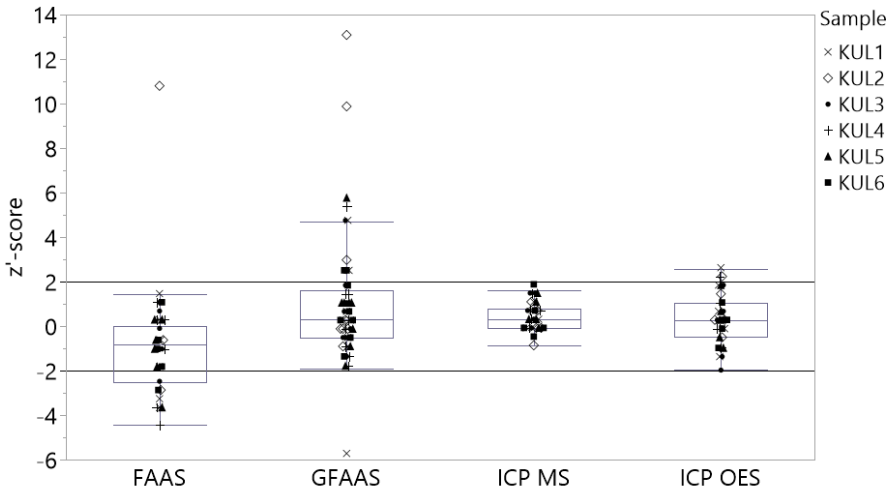


Figure 2. Z'-scores of the participating laboratories in Latin America for the different equipment that was used to analyse Cd in the six cacao samples). A score of |z'| ≤ 2 was considered acceptable.
Overall, it is clear that Inductively Coupled Plasma Mass Spectrometry (ICP-MS) has the best performance, followed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-OES) and by Atomic Absorption Spectroscopy (FAAS and GFAAS). AAS especially falls off for the sample with the lowest Cd concentration (KUL 2, x_{pt} = 0.094 mg kg^{-1}).

Along the same lines, a proficiency test was set up on **soil Cd concentrations**. Details are given in the interim report of 2022 (**Annex 2**). Four soil samples (two from Belgium, one from France and one from The Philippines) were distributed to all participants. The analytical results obtained by each participant were compared to consensus values because no reference values were available for these samples. Laboratory results were rated using z(')-scores in accordance with ISO 17043(2010) and ISO 13528(2015).

For the sample with the lowest Cd concentration (median 0.060 mg kg^{-1}), satisfactory results were obtained by 11 out of 24 participants (46%). Six of the laboratories reported the concentration in that sample as below their limit of quantification. The sample with the highest number of satisfactory results (median 1.6 mg kg^{-1}) was adequately measured by 21 out of 24 laboratories (88%). Overall, the results for the 24 laboratories can be summarized as:

- 5 laboratories reported acceptable Cd results for all samples: z(')-scores between -2 and 2, roughly equivalent to within 2 times the Horwitz standard deviation which was equivalent to 15-22 % of the median values.
- 5 laboratories reported acceptable results for all samples except for sample KUL 10, which had a very low Cd concentration (median 0.060 mg kg-1).
- 2 laboratories reported acceptable results but all z(')-scores were systematically above or below zero, i.e. a bias.
- 2 laboratories had a bias and reported unacceptable results for sample KUL 10.
- 2 laboratories reported acceptable results except for one sample (not KUL 10).
- 3 laboratories had a bias and reported one unacceptable result or reported 2 unacceptable results.
- 1 laboratory had a bias and reported 2 unacceptable results.

- 4 laboratories reported unacceptable results for (almost) all samples and had a possible bias.

Each laboratory received a certificate of participation and an individual laboratory report with recommendations and comments. An example of a certificate is added in **Annex 3**. A general individuals lab report is added in **Annex 4**.

The results of the inter-laboratory proficiency tests clearly demonstrated substantial variability in analytical performance across laboratories, particularly at low Cd concentrations, and highlighted gaps in quality control procedures, sample preparation, and instrument calibration. These findings were used as the basis for designing tailored capacity-building support.

The project team developed written guidelines on best laboratory practices for the determination of Cd in cacao beans and soils, aligned with international standards (ISO 13528 and ISO 17025) (**Annex 11**). The guidelines covered key aspects such as sample preparation and homogenization, choice of analytical technique, calibration and quality control procedures, use of certified reference materials, blanks and replicates, and reporting of results. These documents were shared with all participating laboratories and relevant national institutions.

In parallel, targeted laboratory training sessions were organized for technical staff from participating laboratories in Colombia and Ecuador (**Annex 9 and 10**). These trainings combined theoretical guidance with practical demonstrations and focused on improving analytical accuracy, precision, and quality assurance using the equipment available in each laboratory. In addition, each laboratory received an individual performance report with specific recommendations based on its proficiency test results. Selected laboratories also benefited from hands-on follow-up support, including live troubleshooting and mentoring on sample preparation, instrument settings, and quality control practices.

Together, the development of harmonized guidelines and the delivery of tailored training and feedback contributed to measurable improvements in laboratory awareness, analytical consistency, and readiness for accreditation or certification processes. This activity directly addressed a critical institutional gap identified at project inception and strengthened the foundation for reliable Cd surveillance in the cacao sector.

4.2.2 Variability in Cd concentration among ready-for-sale cacao beans

In order to study the uncertainty in Cd concentration of cacao samples, three different sources of variance were considered: (1) the analytical variance, (2) the natural variance *among* individual beans in a bag, and (3) the variance in Cd concentration *among* bags. Different sampling schemes were used to estimate these variance components as described in the paper that we wrote on this study (Dekeyrel et al. 2023, **Annex 5**). The uncertainty in Cd concentration of a sampling scheme involving different replicates is then a function of these three sources of variability.

Beans were collected from four commercial lots in different cacao warehouses in the province of Guayas, Ecuador, in September 2021. A commercial lot consists of several wooden pallets, each containing 30 jute bags containing approximately 70 kg of beans. Each commercial lot contained beans originating from multiple farms. In the warehouses, beans were manually or mechanically mixed before bagging according to local practice.

First, analytical (normalized) variance was recorded, either from duplicate analyses of ground beans in the same laboratory (148 duplicates) or from the triplicate analyses of the six cacao samples measured by the 23 laboratories in Latin America that participated in the inter-laboratory test. The mean CV of the two independent datasets was strikingly similar, i.e., both were **5 %**. Second, sampling showed that bean number effects on variance obeyed the rule that it decreases with 1/number of beans (n) or CV decreased with $1/\sqrt{n}$. A sample size of n = 60 decreased the mean **CV < 15** % (Figure 3) the threshold chosen based on the allowed variation in inter-laboratory tests as discussed in more detail below.

The second hierarchical sampling allowed to further identify the variance among beans and among bags on a pallet. This shows that an about equal variance is found among a random sample of 60 beans within a bag and among bags from which that sample is taken.

For the simulations of bean sampling strategy, a prediction was made for several possible sampling strategies, details of the modelling are in the paper in **Annex 5** and a summary given in Table . The simulations predict that the CV is more affected by the number of beans for an analytical sample in the commonly used range between 10 - 60 bean than by the number of bags from which a mixed sample is taken. To decrease the CV below 15%, 60 beans should be sampled. It confirms the overarching effects of number of beans followed by the number of bags and only minor effects of requesting more analytical replicates from a sample of ground beans. According to this simulation, collecting the composite sample from five bags is already sufficient.

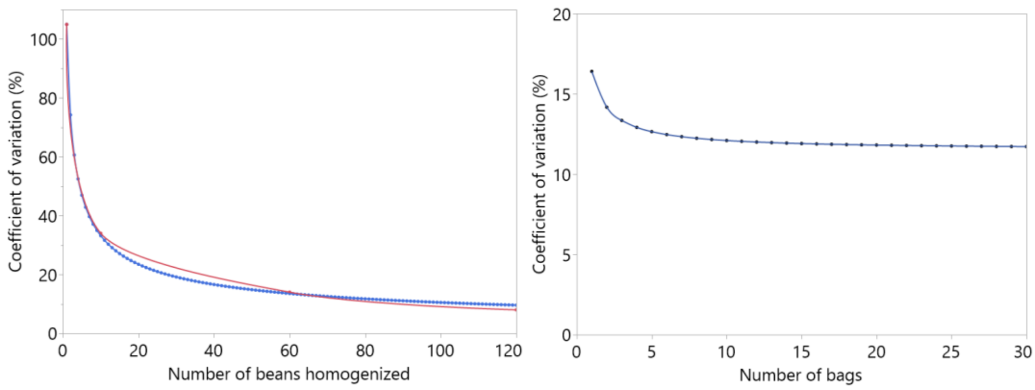


Figure 3. Measured and simulated effects of sample sizes on the coefficient of variation (%) of bean Cd concentrations in a commercial lot. The left figure gives the CV for only one bag sampled but in which number of beans before grinding and analysis is varied. The red line indicates the measured values (for n = 1, 10, 60 and 120) and the blue line gives the theoretical values with the CV decreasing with $\sqrt{n}$ starting from the measure value of CV = 105 % for n = 1. The right figure gives the CV for a random sample of 60 beans collected from a number of bags for realistic worst-case components of variances that were derived from the hierarchical sampling.

Table 2. Prediction of the variance and the CV of different possible sampling strategies. Strategies 1 and 2 are based on the two strategies that were carried out on the four pallets (see further).

Strategy	# beans	From # bags	Number of chemical analyses on the ground beans	Predicted total variance	Predicted CV (%)
1	10	20	1	0.069	26
2	60	20	1	0.014	12
3	120	20	1	0.0084	9
4	60	10	1	0.014	12
5	60	5	1	0.016	13
6	60	20	2	0.014	8

Two practical sampling strategies were tested on one pallet of each of the four commercial lots. For sampling strategy 1, 30 beans were taken from 20 bags of one pallet and 10 beans were ground after manually mixing. Strategy 1 resulted in an average CV of 24 % and a maximum CV of 34 % (Table 3). Strategy 2 was similar to the first, but 60 beans were ground. This resulted in an average CV of 10 %, with a maximum CV of 16 %. These values are close to the simulated values for strategies 1 and 2 in Table 3. Again, the difference between the two strategies highlights the importance of homogenizing a sufficient number of beans.

Table 3. Coefficients of variation for the two different sampling strategies that were tested. For strategy 1, 30 beans were taken out of 20 bags of one pallet for a total of 600 beans. These beans were manually mixed for 5 minutes and then 10 beans were taken out and homogenized in a coffee blender. Strategy 2 was similar, but 60 beans were homogenized in a coffee blender. Both strategies were done in triplicate. All chemical analyses were only performed once. Each of these strategies was tested on four commercial lots and the minimum and maximum CVs represent the range found for the different lots.

Strategy	# beans	From # bags	Number of chemical analyses on the ground beans	Measured CV (%)			Predicted CV (%)
				Average	Min	Max	
1	10	20	1	24	16	34	26
2	60	20	1	10	5	16	12

Strategy 2 generally ensures obtaining a CV < 15%, a threshold similar to the modified Horwitz equation described in ISO 13528 (2015). That equation allows an inter-laboratory variation of 15 to 17 % for Cd concentrations within the relevant range (0.5 to 1 mg kg^{-1}). A variation of 15 % would also mean that 97.5 % (two standard deviations) of all commercial lots would have a Cd concentration below 0.78 mg kg^{-1} when the mean measured Cd concentration of a lot is 0.6 mg kg^{-1}. The fine flavour cacao beans from Latin America are mainly used to make (single-origin) dark chocolate. The limit imposed by the European Commission on chocolates containing ≥ 50 % dry cacao solids is 0.80 mg kg^{-1}. This lot could therefore still be used to make dark chocolate that conforms to the EU limits. Stricter limits, e.g., 0.10 mg kg-1 on chocolate containing up to 30 % cacao solids, are less relevant because the flavour profile is less important for milk chocolates, and low-Cd beans from other producing regions, like Ivory Coast and Ghana, are more often used to make this type of 'bulk' chocolate.

4.3 Output 2: Improve mapping baselines and mapping capacity for zoning of vulnerable areas in the two countries, based on harmonized methods and data on Cd levels in cacao beans

This output was carried out in close collaboration with the Clima-LoCa Project, funded by the European Union. This project also included a mapping activity. It was therefore more effective to combine the activities of both projects because prediction accuracy increases with the amount of samples taken. A map of Cd concentrations in cacao beans was developed for cacao-growing areas and areas with potential for cacao expansion of Colombia and Ecuador. The map was produced at spatial resolution of 30 meters using a harmonized approach based on machine learning (ML) that models the relationship between the target variable (Cd) and geospatial covariates (predictors).

The data used for mapping consists of 77 geospatial covariates (**Annex 6**) and field and laboratory data from 3065 site locations. Of these, 2133 were sampled jointly by Clima-LoCa (1882) and this STDF project (251), while an additional 932 data points were shared by other projects. All samples were collected following the Clima-LoCa Protocol and a gap-filling sampling strategy that considered current cacao production areas, data-deficient regions, and sites representative of the region's geomorphology. Laboratory analyses of Cd in soils and beans were conducted using ICP-MS at KU Leuven and the University of Nottingham. Other physicochemical soil properties were analyzed within each participating country.

Since Cd concentrations in cacao beans in this region are correlated with Cd contents in the soil (R^2= 0.69) and its interaction with other soil properties, we developed digital soil maps of total Cd, pH, soil organic matter (SOM), clay, calcium (Ca), cation exchange capacity (CEC), available potassium (K), available manganese (Mn), total phosphorus (P), and available zinc (Zn) to be used as additional covariates to map Cd in beans.

For soil mapping, we used the Digital Soil Mapping (DSM) approach (Jenny, 1941; McBratney et al., 2003), which models the relationship between soil data and geospatial covariates (**Annex 6**) representing key soil-forming factors such as climate, vegetation, topography, and parent material. The DSM model employed was the ML algorithm Quantile Random Forest (QRF), implemented using the *quantregForest* package in R. QRF is an extension of the Random Forest (RF) algorithm that enables the estimation of conditional quantiles, providing both central tendency predictions (mean) and the associated uncertainty. For mapping Cd in beans, we applied the same methodology and covariates used for mapping soils.

We trained the QRF model with over 100 iterations for both Cd in soils and beans to assess model stability and predictive performance. In each iteration, the dataset was randomly split, with 70% used for training and 30% for validation. Model training employed 5-fold spatial cross-validation to account for spatial dependence. Hyperparameter tuning was performed using a random search strategy, testing 100 combinations per iteration across four key hyperparameters (e.g., number of trees, mtry). To identify the most relevant predictors based on their contribution to model accuracy and variable importance we used VSURF method.[10] The most important covariates identified for predicting the spatial variability of Cd in soils were Zn, SOM, Mn, pH, sulfur dioxide, gross primary production, precipitation, temperature, landforms, and slope. Meanwhile, for Cd in cacao beans, the covariates that explained the greatest variability included the predicted Cd concentrations in soils (derived from soil properties), as well as geospatial covariates such as latitude, longitude, distance to mining areas, and atmospheric carbon monoxide. These covariates reflect both edaphic and environmental drivers influencing Cd variability in the cacao beans.

Model performance was assessed across all iterations using the validation subset (30% of the data). The optimal model was selected based on standard regression metrics: lowest Root Mean Squared Error (RMSE), highest Coefficient of Determination (R^2), and lowest Mean Absolute Error (MAE). For Cd in soils, the best model had RMSE of 0.90 mg/kg, $R^2$of 0.50, and MAE of 0.31 mg/kg. For Cd in beans (Figure 4), the corresponding was RMSE=1.45 mg/kg, R^2 = 0.61, and MAE = 0.75 mg/kg. In addition, predictive uncertainty was quantified using the interquartile range (i.e., the difference between the 95th and 5th percentiles), offering a spatially explicit measure of prediction confidence (Figure 4).

[10] Robin Genuer, " VSURF: An R Package for Variable Selection Using Random Forests", *The R Journal 7, no.2, (2015)*

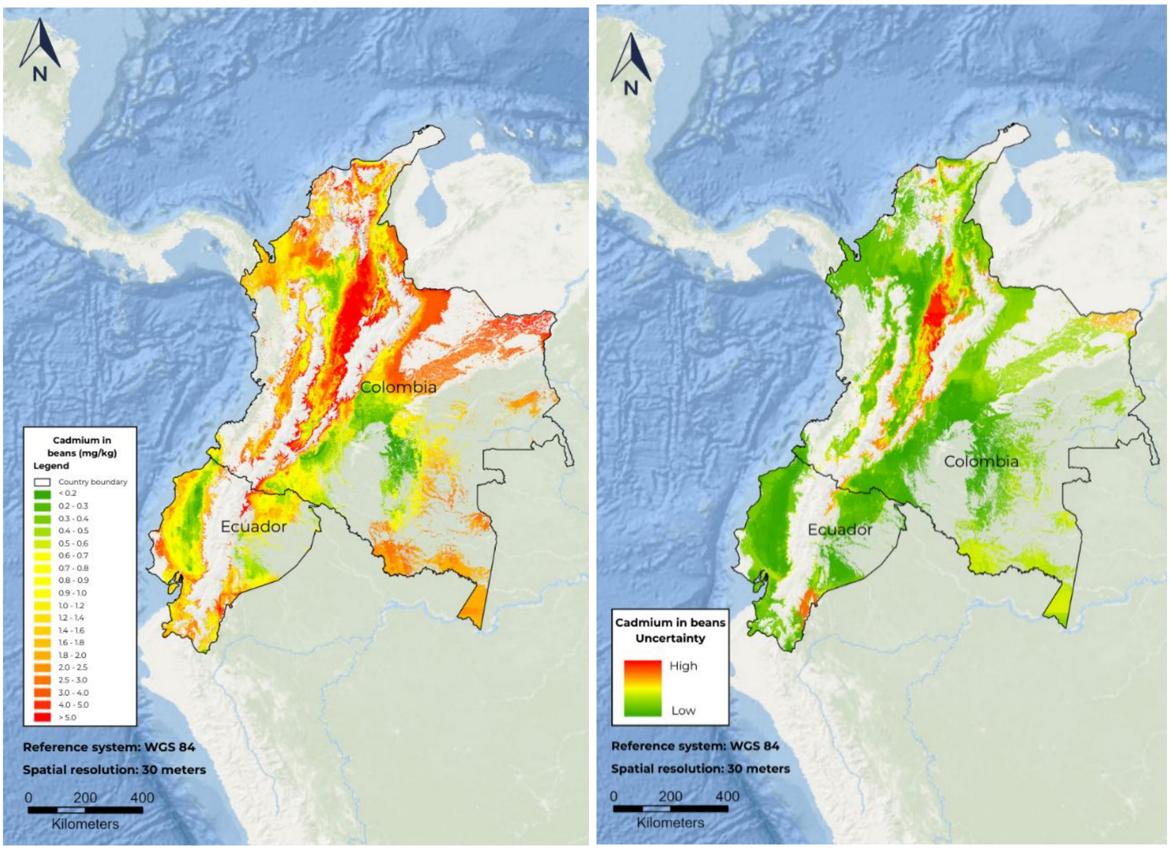


Figure 4. The digital map of bean Cd concentrations in Colombia and Ecuador (left) was constructed with the joint efforts of several projects, including this STDF project. The uncertainty map is shown on the right.

The map shows the spatial distribution of predicted average Cd concentrations in cacao beans (mg/kg) across Colombia and Ecuador. While most cacao-growing areas in Ecuador exhibit relatively low Cd levels (0.06–0.5 mg/kg, shown in green), significantly higher values are predicted in parts of Colombia, particularly in the central Andean region (north of Cundinamarca, west of Boyacá and south of Santander departments). In these localized zones, our field sampling and models showed Cd concentrations in beans exceeding 5.0 mg/kg, reaching up to 21.0 mg/kg in some cases (indicated in orange and red). These high-value zones are also areas of greater model uncertainty, likely due to the high soil variability, the complex topography, and limited sampling density, and coarse scale of geospatial information. These areas could be prioritized for future sampling to improve the precision of local estimates and get a better understanding of the distribution of the Cd concentration in this region.

The analysis showed that the spatial distribution of Cd is mainly influenced by geology, landform, slope, climate, and other soil properties. The highest Cd concentrations in beans (>5 mg/kg) were found in lower slope areas with tropical rainforest climate and clay loam soils, likely developed from sedimentary rocks. Although some agricultural inputs may contain traces of Cd, the results indicate that these are not the main cause of Cd in cacao; geology appears to be the predominant factor especially in locations where shales have been the main geological formation. Soils developed from shales often contain naturally higher levels of Cd due to the metal's presence in the parent material. As these rocks weather over time, Cd is released into the soil, where it can be taken up by cacao plants, especially under certain soil conditions such as low pH or high clay content. This geological influence helps explain why some cocoa-growing regions, particularly those with shale-rich formations, exhibit higher Cd concentrations in beans.

4.4 Output 3: Develop scientifically sound and context-relevant guidelines on good agricultural practices that lower Cd levels in cacao

The effectiveness of different soil amendments for reducing bean Cd were tested in 10 different field trials (36-60 months duration) in Ecuador. The experimental farms (n = 10) were selected in different cacao producing areas in Ecuador where Cd concentrations were above 1 mg kg^{-1} in the bean. The majority of these farms were part of collaborative projects with the industry. The first farms were implemented in the scope of the former VLIR project that KUL and ESPOL conducted between 2017 and 2022. The funding from STDF was used to make a meta-analysis of all the field trials. The idea here is that this meta-analysis could identify good agricultural practices (GAP) and that guidelines may come out of this meta-analysis.
In general, treatments were applied to alter the following soil chemical characteristics or plant nutrients:

- Increase soil pH = calcium carbonate (lime)
- Increase soluble soil Ca = calcium sulphate (gypsum)
- Increase soil organic matter = compost or biochar
- Increase plant iron, zinc or manganese = soil application of Fe, Zn, Mn, in EDTA-K-Mn/Fe/Zn.
- Increase soil/plant silicon = Potassium silicate
- Fertilizer = mixed mineral nutrients to increase plant yield

To test whether the effect of the treatment is dose-dependent, some of the treatments were applied at two dosages on the same farm. Most treatments were applied directly to the soils after removing the litter. Only the micronutrient treatments (Fe, Zn and Mn) were first applied to the leaves (4 applications) before switching to soil application. Plant samples were taken every 6 months, and soil samples once per year. The first monitoring of the farms occurred 6 months after treatments were applied.

An overview of the average effectiveness of the soil amendments for reducing bean Cd is given in Figure 5. The effectiveness is expressed in terms of Reduction Factors, which are calculated for every treatment replicate relative to the corresponding control replicate with RF $Cd_{control,replicate\ X,\ time}$ /$Cd_{treatment,\ replicate\ X,\ time}$. Consequently, a reduction factor of 1 means that there is no difference in bean Cd compared to the control, while a reduction factor of 2 corresponds with a 50% reduction in bean Cd concentration. In Figure 5, data from all the farms at and beyond 18 months after application onwards is used because it was previously shown that bean Cd does not yet respond within the first year after soil amendment due to the large reservoir of Cd in the tree and the slow migration of the soil amendments in the rooted soil.

For four types of treatments, the site and harvest mean reduction factors are significantly higher than 1, i.e., at a large scale, we can state that the soil amendments significantly reduce bean Cd concentrations were observed, namely for compost, gypsum ($CaSO_4$), lime ($CaCO_3$), and fertilizer. However, the reduction factors are low, and only the fertilizer treatment had a reduction factor higher than 1.2. The fertilizer treatment (RF=1.3) was only used at two farms; consequently, those results cannot be extrapolated to Ecuadorian soils in general.

Taken together, these results did not show a large and/or consistent effect of the soil amendments in reducing bean Cd. The RFs found are small compared to the cost of soil amendments, and it is clear that the strategies of mixing high Cd with low Cd beans (goal 1) are much more effective in dealing with the regulations; the same is true for the correct selection of cacao expansion areas (goal 5).

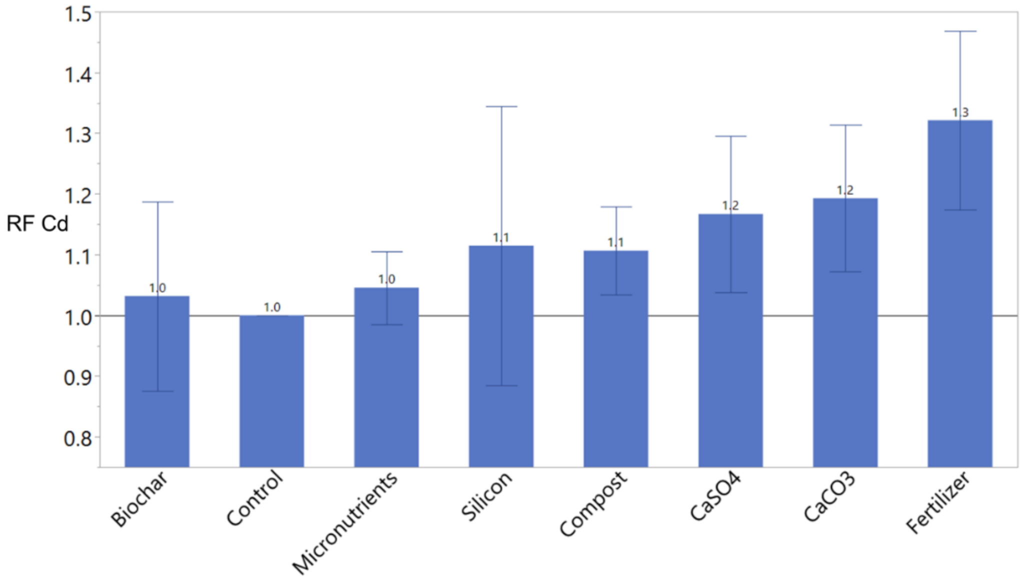


Figure 5. The meta-analyses of ten field trials in Ecuador with the effects of soil amendment in reducing the bean Cd concentrations. The data is the mean Cd reduction factor (RF= $Cd_{control}/Cd_{treatment}$) for each treatment (data from high and low application rates are merged), and the bars give the 95% confidence interval of the means. Only data from 18 months onwards is used as earlier data is not yet influenced by the soil applications, i.e. at 6 and at 12 months after application. Only Compost (n= 9 farms), Gypsum ($CaSO_4$, n=7 farms), lime $CaCO_3$, n=4 farms) and Fertilizer (n=2 farms) have reduction factors with a 95% confidence interval above 1.

Contrary to the initial project description, a guide/handbook was not written as part of this Output. It was felt that no substantial new information was available during the project, and many publications on agricultural practices were already available. Therefore, we focused our remaining time and resources and more relevant topics (see Outputs 4 and 5), as explained above.

4.5 Output 4: Test a new benchtop XRF based equipment for fast screening of Cd concentrations in nibs, soil and leaves

The conventional acid digestion followed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is time-consuming and expensive. X-ray Fluorescence (XRF) is a non-destructive, alternative technique that offers speed, cost, and ease of use advantages. In the past, relatively high detection limits impeded its ability to compete with ICP-MS for Cd analyses. However, new optimizations tailored for heavy metal detection drastically lowered these limits. This study explores the potential of a recently optimized Monochromatic Energy Dispersive X-ray Fluorescence (MEDXRF) as an alternative to ICP-MS for measuring Cd concentrations in cacao, leaf, and soil samples. The MEDXRF equipment used in this study is the E-max Portable Heavy Metal Analyzer for Soil and Food (Z-Spec, East Greenbush, NY, USA), a recently developed commercially available desktop instrument.

In total, 112 bean, 19 cacao liquor, 75 leaf, and 108 soil samples were analyzed by both techniques, which resulted in a high accuracy and precision, the relationship ICP-MS data (x) and MEDXRF (y, both in mg Cd kg^{-1})) was $y = 1.013\ x + 0.004$, $R^2 = 0.984$, Figure 6). For a measurement time of 200 s, the coefficient of variation (CV) among three replicates increased above 15 % around a Cd concentration of 0.1 mg kg^{-1}, indicating that care should be taken below this concentration. Additionally, a significant difference in CV was obtained between soils sieved over 500 µm soil samples (median 8.2 %) or 2 mm soil samples (median 9.8 %). However, no significant difference in CV was observed between 500 µm unpeeled beans and 20 µm peeled beans (cacao liquor). The proposed protocol based on this data is to analyze three replicates for 200 s with a sample size of 500 µm. The optimized MEDXRF technique offers advantages in terms of cost-effectiveness and efficiency for routine monitoring in the cacao supply chain, large-scale screening, and scientific research.

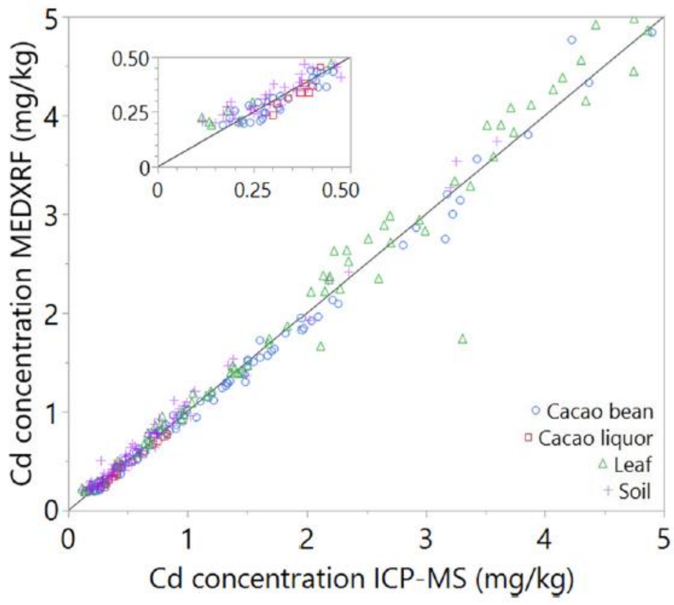


Figure 6. The Cd concentration measured by MEDXRF in function of the Cd concentration measured by ICP-MS for different sample types (o cacao bean, ☐ cocoa liquor, Δ cacao leaf, + soil), both in mg kg^{-1}. The diagonal black line represents the 1:1 line.

More details on this new equipment can be found in scientific paper that was published (**Annex 7**). The optimized MEDXRF technique offers advantages in terms of cost-effectiveness and efficiency for routine monitoring in the cacao supply chain, large-scale screening, and scientific research. It allows blending high with low Cd beans and allows exporting lots that meet the thresholds set by commercial buyers. The implementing agencies have published that method and have disseminated the information; we know that this equipment has now been bought in Ecuador and Colombia by research and commercial partners.

4.6 Output 5: Explore the potential of mechanistic geochemical models to predict Cd availability in soils and Cd accumulation in beans and evaluate the best method for predicting bean Cd concentrations in areas where cacao is not yet planted based on soil map data or on soil analyses

The potential to use geochemical models to predict Cd availability in soils and Cd accumulation in beans and explain the underlying mechanisms was explored. This work was the result of close collaboration between Wageningen University, KU Leuven, ESPOL University in Ecuador and CIAT in Colombia and will be published in 2025 as part of a PhD thesis and submitted to a peer reviewed scientific journal. We used existing data and soil samples collected as part of previous projects and the ongoing Clima-LoCa project and complemented the data base, with additional soil analyses that were performed at KU Leuven. STDF funds were used for the laboratory analyses, and for the time investment of KU Leuven and WUR staff involved in the modelling study.

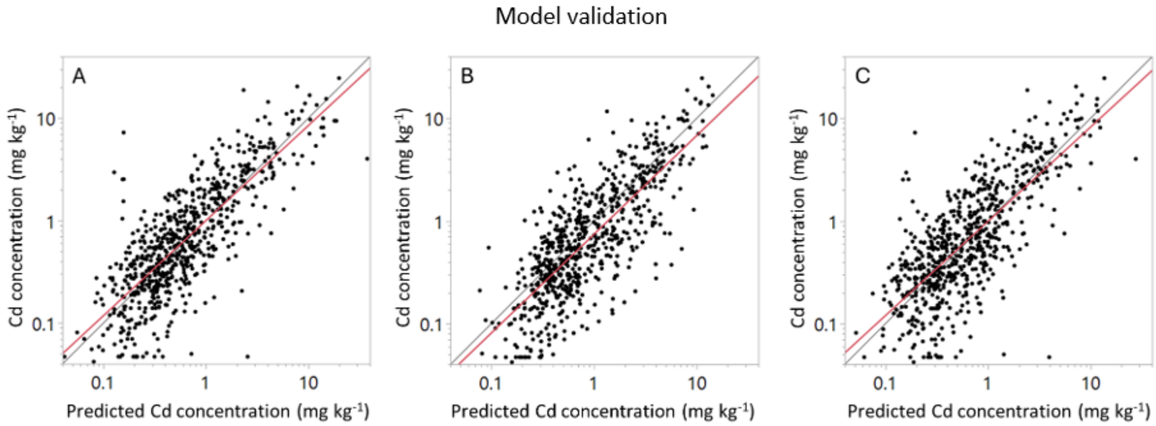
The study made use of a dataset that consists of 188 paired soil-plant samples representing diverse cacao growing conditions in Ecuador and Colombia. We quantified the ability of geochemical multisurface models (in Orchestra software) with various levels of model complexity to predict Cd concentrations in the soil solution (available Cd) and the Cd levels cacao beans and leaves, as well as the Cd transfer factor (Cd leaf:Cd soil and Cd bean:Cd soil). Furthermore, we used the model to explain variation in the Cd transfer factor within our dataset, based on geochemical mechanisms related to solid-solution partitioning and speciation of Cd in soil.

Key findings include:

- Most variation in cacao bean Cd (73%) and leaf Cd (82%) could be explained by indicators of Cd intensity in the soil solution, either measured in a 0.001 M $Ca(NO_3)_2$ extraction or predicted with the model.
- The model further provided mechanistic insights, showing that soil pH was the key factor governing the solid-solution partitioning and speciation of Cd in soil, as well as the soil-plant Cd transfer factor. We also found that Cd accumulation in cacao tissues is more strongly related to Cd that is electrostatically (weakly) bound to clay and organic matter than to Cd specifically bound to functional groups of organic matter or metal oxides. This indicates that the capacity of soils to buffer the solution Cd concentration is an important factor determining Cd uptake and challenging its mitigation.
- Simplification of the geochemical models used had a negligible influence on model performance or the predictive ability for Cd in cacao, thus showing the potential to apply the models with basic soil data that can be obtained routinely in most laboratories.
- In conclusion we showed, for the first time, that employing geochemical multi-surface models is a feasible approach for Cd risk assessment in cacao growing areas, and also provides mechanistic insights on the underlying mechanisms. Such insights are of key importance to design more context-specific mitigation strategies for Cd in cacao considering local soil conditions. To this end the model could be used to explore the potential of different management scenarios aimed at manipulating soil properties that affect Cd dynamics, such as use of soil amendments or phytoremediation. Further work is recommended to make the models more accessible to be used more widely among stakeholders.

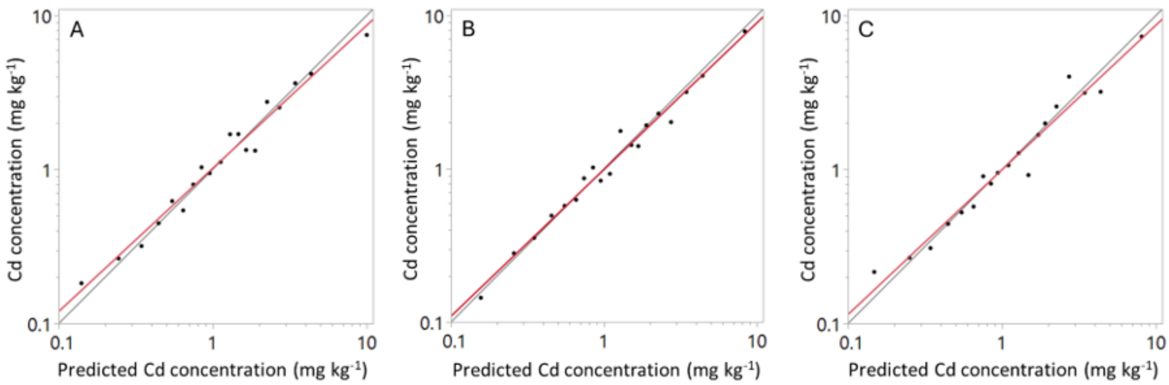
The final part of the STDF project evaluated three approaches (models) to estimate the Cd concentration in cacao beans in cacao expansion areas, i.e., either based on a digital soil map predicting bean Cd concentrations or based on local soil analyses followed by a statistical or a semi-mechanistic model to predict Cd uptake in cacao. The three models had been calibrated on a large dataset (n = 2317-2663) of paired soil–bean samples collected across Ecuador, Colombia, and Peru. The validation was made on 691 paired soil-plant samples in Ecuador and Colombia that had not been used for model calibration. All models showed similar predictive performance for individual points, with R^2 values on log-transformed concentration data ranging between 0.57-0.64, depending on the model, but an unacceptably wide confidence interval equivalent to a factor of about 4 of the prediction (Figure 7). However, regional mean Cd concentrations were well predicted: when outputs were grouped into fixed concentration intervals, observed means matched predicted means with an R^2 of log-transformed values ranging from 0.97-0.99 (Figure 8). The digital soil map (Figure 4) predicted regional mean Cd concentrations within a factor of only 1.2 higher or lower in the most relevant range of bean Cd between 0.30-1.20 mg Cd kg kg^{-1} (Figure 8). These demonstrate the potential of digital soil maps for regional Cd risk assessment and suggest that predicting mean bean Cd concentrations across spatial or logistical clusters, such as cooperatives, may be more effective than field-level point predictions based on soil data.

This STDF project also spent time on training in digital soil mapping, with due attention to gender distribution in the trainees: Digital soil mapping training: day 1: n=20 (15 % female), day 2 and 3: n=22 (23 % female), day 4: n=19 (16 % female), day 5: n=17 (18 % female).



	R^2 = 0.64	R^2 = 0.62	R^2 = 0.57
	RMSE = 0.33 log-units	RMSE = 0.34 log-units	RMSE = 0.36 log-units

Figure 7. Measured bean Cd concentrations (in mg kg^{-1}) as a function of predicted bean Cd concentrations (in mg kg^{-1}) for the three predictive methods: multiple linear regression (A), digital soil mapping (B), and mechanistic modelling (C) for all datapoints in the validation dataset (n = 691). The 1:1 line is indicated as a black line, and the predicted-observed trend as a red line.



	R^2 = 0.97	R^2 = 0.99	R^2 = 0.96
P/O ratios between 0.3-1.2 mg Cd/kg	0.8-1.2	0.8-1.2	0.8-1.1

Figure 8. Mean measured bean Cd concentrations (in mg kg^{-1}) as a function of mean predicted concentrations (in mg kg^{-1}) for the three predictive methods: multiple linear regression (A), digital soil mapping (B), and mechanistic modelling (C). Each point represents the average of all validation samples within fixed prediction intervals based on the digital soil mapping predictions. The 1:1 line is indicated as a black line, and the predicted-observed trend as a red line.

4.7 Other unexpected results

The cacao prices have increased almost factor of four during this project (Figure 9) which has sparked the expansion of cacao in Latin America and interest in predicting the Cd concentrations in these areas (i.e., explaining the new goal 5 of this project). Indeed, cacao production is now more lucrative and countries like Colombia may have interest in cacao whereas Cd may stop that expansion. That is why goal 5 was added: how to predict where this expansion may take place.

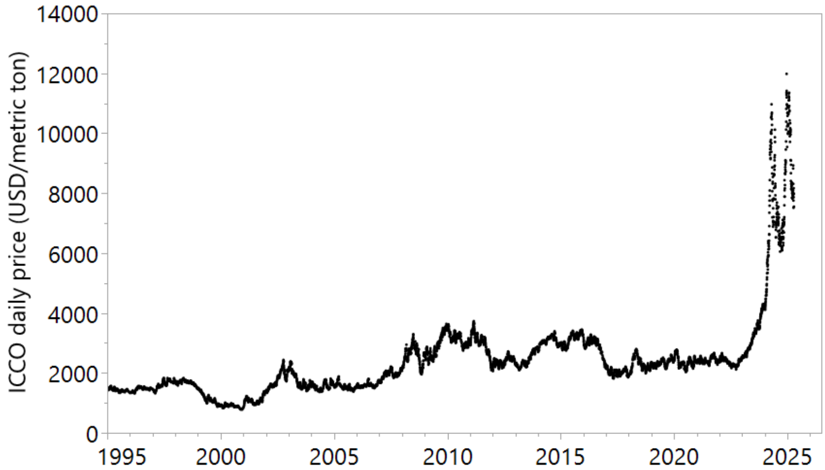


Figure 9. Daily cacao price (in USD per metric ton) from January 1st, 1995 until April 15th, 2025 (adopted from ICCO data).

5. CROSS-CUTTING

5.1 Gender

To prevent the adoption of mitigation measures from being biased by gender, we have been striving for a strong gender balance at the various stages of this project and targeting and monitoring female and male beneficiaries of different capacity-building and dissemination efforts. Awareness of possible gender biases is also essential when dealing with government institutes and decision-makers.

We have made a few statistics to conclude that there was a good gender balance in the people running the project, in the dissemination activities. However, the limited interaction with the decision makers shows a bias towards male participants.

- Project Partners directly involved in decision-making: total n=6 of which 33 % female
- More extended personnel involved (including researchers and financial departments of Project Partners): total n~25 of which ~ 60 % female
- Laboratory training sessions: in total, 98 people participated, of which 60 female (61 %)
- Digital soil mapping training: day 1: n=20 (15 % female), day 2 and 3: n=22 (23 % female), day 4: n=19 (16 % female), day 5: n=17 (18 % female).

5.2 Environment, Biodiversity and Climate Change

This STDF project had been linked to a project that ran together by the same partners: CLIMA-LoCa "Low cadmium and climate-relevant innovation to promote sustainable cacao production in Colombia, Ecuador, and Peru". This regional initiative aimed to support the growing cacao sector in Colombia, Ecuador, and Peru by developing context-specific, low Cd and climate-smart cacao production systems (irrigation and suitable land use). To that end, the project was intended to improve site-specific information, technology development, and knowledge transfer availability. CIAT led the project in collaboration with CIRAD, KU Leuven, Wageningen University, and local universities and research institutes in the three target countries. In that sense, the STDF project has considered the climate change effects on cacao in the maps of land evaluation as a function of projected climate change, i.e. the maps use current climate data as input and can predict the impact of climate change on bean Cd concentrations.

6. FINANCIAL OVERVIEW (MAX. 1 PAGE)

ZKD9073 STDF PG 681

KU LEUVEN & partners

INTERIM REPORT: 8 (FINAL REPORT)

PERIOD: 01.07.2024-31.12.2024

CURRENCY: USD

	STDF	In kind / Other	Total
Total project budget (US$)	516,989.00	101,010.00	**617,999.00**
Total expenditure (US$)	496,859.13	73,814.95	**570,674.08**

Details on the final project budget can be found in the final financial report.

7. CHALLENGES, RISKS & MITIGATION

During the proficiency tests and the laboratory training sessions, we observed that some labs work with very dated instrumentation. Some laboratories did not have access to ultrapure water, making accurate Cd analyses very difficult. Also, even if the available equipment was adequate, a lack of knowledge about the machinery was observed. Additionally, many laboratories did not use certified reference materials (because these materials can be very expensive), limiting the quality control of their reported results. In the end, we feel like a lot of progress was made. Laboratories received personalized recommendations to increase the quality of their analyses, with the equipment available. During the lab training, technicians were not only assisted in improving the quality of the measurements, but also in quality control, i.e. the systematic use of blanks, replicates, and reference materials to ensure accuracy and reliability of results. Additionally, the introduction of the new XRF machine could serve as an alternative to circumvent all these limitations (limited knowledge about the machinery is necessary, no ultrapure water or chemicals needed, etc.).

Once the results of the first activity were obtained (sampling of cacao beans), initial contact with governmental institutions like Ministerio de Agricultura y Ganadería, or MAG, in Ecuador was established. However, communication and interaction proved very difficult. Due to restructuring of the department, we lost our initial contact person, and it proved difficult to get into contact with other personnel. After a failed attempt, STDF was asked for help to establish a new line of communication. On the side of Colombia, governmental institution INM was brought in as an Associate Partner, but later opted out, as mentioned before. It was therefore decided not to pursue the official implementation of sampling protocols for Cd in cacao. Partly because it was not officially part of the Project Description, but mostly because it was concluded that more general sampling protocols that were already in place (i.e. not specifically for Cd, but for other quality control parameters that were already checked, like amount of rocks, pesticides, etc.) were similar enough to our sampling protocol so that no major issues should arise if these samples were also analysed for Cd. The major part of the problem was identified as the laboratories analysing the cacao samples for Cd. Therefore, extra attention was given to receiving and preparing samples during the laboratory training sessions (i.e. making sure that enough beans are ground to get a representative subsample of the receive batch of beans).

The pandemic has slowed down some activities, and this was partly the reason why the no-cost extension to December 2024 had been requested.

For output 3 (agronomic mitigation), there were no meaningful results yet in the field due to a lack of common garden experiments (require > 3 years) and underestimated high variability in the field. Therefore, it was decided to not write a handbook as initially anticipated. We did include some field data, as previously mentioned. Additionally, two extra outputs were created. Both were very relevant to the context of the project, and both resulted in fruitful results for people involved in cacao research and the supply chain (see outputs 4 and 5).

8. COMMUNICATIONS AND OUTREACH

The stakeholders were informed about the cacao Cd problem and mitigation strategies during a hybrid workshop held at ESPOL's campus on March 21st of 2022. In the workshop, the main results from the soil amendment experiments, as well as results from proficiency tests, were presented to stakeholders. A total of 61 participants attended the workshop, 21 in person and 40 online via Zoom (**Annex 8**).

The results of the proficiency tests were disseminated via multiple reports (**Annexes 1, 2, 4**), individual certificates (b), a scientific paper (**Annex 5**) and the laboratory training sessions. The list of participants and some pictures of the training sessions can be found in **Annex 9**. The invitation to the laboratory training is included in **Annex 10**. The manual on good laboratory practices is included in **Annex 11**. This manual was very recently finalized and is yet to be disseminated more. For now, it is shared on the Clima-LoCa platform and shared with the participating laboratories of the proficiency tests.

Dissemination of the final maps will happen in the second half of 2025, as this output was also part of the Clima-LoCa project which is currently still ongoing. The maps in Figure 4 will be disseminated through workshops and infographics. All the maps produced are stored at CIAT Regional Headquarters in Colombia. For now, dissemination mostly consisted of training sessions. The sampling training session by CIAT: video, Facebook post and pictures. The digital soil mapping training: Facebook post and LinkedIn post. **Annex 12** contains the report of the digital soil mapping training.

The effect that the XRF machine will have is still difficult to quantify. Additionally, the Project Partners were also hesitant to promote the machine in incorrect ways, as we cannot act as salespersons for the company, especially since a scientific article was written on the subject (conflict of interest). However, there is definitely interest from both research institutes and stakeholders in the supply chain. An impact story from the Norandino cooperation is attached in **Annex 13**.

9. SUSTAINABILITY & FOLLOW-UP

Efforts were made to integrate the sampling protocol for ready-for-sale beans into official governmental protocols, but, as discussed in the *Challenges, Risks and Mitigation* section, this proved to be difficult and out of the scope of this project.

This project STDF/PG/681 has assisted a similar project STDF/PG/577 led by ICCO and IICA. This project has shared the reference samples of cocoa liquor with the consensus values of Cd concentration. We also processed the data of the laboratories involved in project STDF/PG/577 and provided the implementing agencies with a training that was very comparable to the laboratory training given to the laboratories. All participants of the proficiency tests also have additional samples to use as reference materials; we know this is a method to ensure quality control in their analysis. A large quantity of each sample was produced and free additional samples can be shipped to every laboratory that requires them. Additionally, the Clima-LoCa project is organizing a second round of proficiency tests to check progress in laboratory performance and provide the laboratories with more reference materials.

Most importantly, the recent demonstration of the value of digital soil mapping represents a significant advancement for the expanding cacao sectors in Ecuador and Colombia. This method has proven effective in accurately predictingloc bean Cd concentrations without the need for labour-intensive and costly soil sampling, making it especially valuable for identifying suitable new areas for cacao cultivation. As such, it offers a practical and scalable tool to support field selection, investment decisions, and regulatory compliance. Beyond its technical merits, the approach is expected to inform both policy development and strategic planning, ultimately contributing to more sustainable and Cd-compliant growth of the cacao industry in the region.

In parallel, the introduction of new portable XRF equipment offers additional benefits. These instruments enable rapid and low-cost Cd measurements in the field, supporting both the identification of suitable expansion areas and improved monitoring across the supply chain. Together, the predictive maps and field-based XRF analysis provide complementary tools to guide bean selection and blending strategies aimed at meeting regulatory Cd limits in cacao products.

10. LESSONS LEARNED

The project successfully demonstrated the value of digital soil mapping and portable XRF technology as innovative tools for predicting and monitoring Cd in cacao beans. These tools reduced reliance on traditional soil sampling and costly laboratory analysis, offering efficient methods for identifying suitable cacao expansion zones and for routine quality control. Additionally, working closely together with many local laboratories in both countries ensured that protocols, data harmonization, and capacity building could be developed and shared more effectively. Personalized feedback on lab training led to measurable improvements in analytical performance across participating laboratories. Furthermore, the analysis showed that the spatial distribution of Cd is influenced by geology (especially from sedimentary rocks), landform, and soil properties. Geochemical multi-surface models proved feasible for Cd risk assessment, providing insights on the underlying mechanisms, essential to design context-specific mitigation strategies. Efforts to formally embed sampling protocols into national systems proved challenging due to institutional restructuring and limited engagement from some government stakeholders. Similarly, the expected results from field-scale agronomic trials (e.g., soil amendments) were more limited than anticipated, primarily due to high field variability and long response times, highlighting the difficulty of using agronomic interventions as a standalone solution.

On a more personal note is

1. the observation that this project is the result of joint work and that there has been great commitment and involvement of all implementing partners;
2. that there has been very good coordination and collaboration with other ongoing projects to ensure synergies.

11. RECOMMENDATIONS

The cacao sector and governmental agencies should use the digital soil maps as a guide when looking for expansion areas and to avoid areas with > 2 mg/kg at all cost, especially for the production of beans meant for export. The XRF machine is recommended for fast and low-cost monitoring. Both techniques are complementary and can help tremendously in making sure that cacao for export meets the regulations and/or demands of the buyer.

To accurately quantify the Cd of a batch that is ready for export (e.g. a pallet of 2-3 metric tons), a composite sample from at least 10 bags on a pallet, and at least 60 beans should be ground before analysis to obtain an acceptable coefficient of variation below 15%.

To ensure sustained progress in analytical quality, national authorities should promote the routine use of reference materials (preferably certified ones), inter-laboratory proficiency testing, and continued training. Laboratories should be incentivised to use better quality control through a centralized certification system and should be supported in doing so. The XRF machine can serve as an alternative for Cd analysis in laboratories, but care should be taken because this method is much more limited in the amount of elements it can accurately analyse.

The mapping exercise suggested that the high Cd areas (high soil Cd, e.g. in Colombia) could be prioritized for future sampling to improve the precision of local estimates and get a better understanding of the distribution of the Cd concentration in this region. Further work is also recommended to make the geochemical multi surface models more accessible to be used more widely among stakeholders

Future projects should prioritize early and consistent coordination with public institutions to embed outcomes in national systems. Establishing focal points within ministries or regulatory agencies could improve follow-through and long-term alignment with SPS priorities.

12. ANNEXES

- Annex 1: Final report cacao proficiency test
- Annex 2: Final report soil proficiency test
- Annex 3: Example of certificate of participation proficiency test
- Annex 4: Example of individual laboratory report proficiency test
- Annex 5: Scientific publication on sampling and laboratory variability
- Annex 6: Geospatial covariates used in digital soil mapping
- Annex 7: Scientific publication on XRF equipment
- Annex 8: dissemination of sampling and laboratory variability results
- Annex 9: List of participants in laboratory training sessions + pictures
- Annex 10: Invitation for laboratory training sessions
- Annex 11: Laboratory guidelines for good lab practices and quality control
- Annex 12: Digital soil mapping training report
- Annex 13: Impact story XRF equipment
- Annex 14: Final signed financial report

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